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# The kinematic and hydrographic structure of the Gulf of Maine Coastal Current

Neal R. Pettigrew[a,?], James H. Churchill[b], Carol D. Janzen[a], Linda J. Mangum[a], Richard P. Signell[c], Andrew C. Thomas[a], David W. Townsend[a], John P. Wallinga[a], Huijie Xue[a]

[a] *School of Marine Sciences, University of Maine, Orono, ME 04469, USA*
[b] *Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA*
[c] *United States Geological Survey, Woods Hole, MA 02543, USA*

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## Abstract

The Gulf of Maine Coastal Current (GMCC), which extends from southern Nova Scotia to Cape Cod Massachusetts, was investigated from 1998 to 2001 by means of extensive hydrographic surveys, current meter moorings, tracked drifters, and satellite-derived thermal imagery. The study focused on two principal branches of the GMCC, the Eastern Maine Coastal Current (EMCC) that extends along the eastern coast of Maine to Penobscot Bay, and the Western Maine Coastal Current (WMCC) that extends westward from Penobscot Bay to Massachusetts Bay. Results confirm that GMCC is primarily a pressure gradient-driven system with both principal branches increasing their transport in the spring and summer due to fresh-water inflows, and flowing southwestward against the mean wind forcing during this period. In the spring and summer the subtidal surface currents in the EMCC range from 0.15 to 0.30 $\mathrm{m\,s^{-1}}$ while subtidal WMCC currents range from 0.05 to 0.15 $\mathrm{m\,s^{-1}}$. The reduction of southwestward transport near Penobscot Bay is accomplished via an offshore veering of a variable portion of the EMCC, some of which recirculates cyclonically within the eastern Gulf of Maine. The degree of summer offshore veering, versus leakage into the WMCC, varied strongly over the three study years, from nearly complete disruption in 1998 to nearly continuous through-flow in 2000. Observations show strong seasonal and interannual variability in both the strength of the GMCC and the degree of connectivity of its principal branches.

*Keywords:* Gulf of Maine; Coastal current; Seasonal variability; Interannual variability; Cyclonic gyres; Offshore current veering

## 1. Introduction

The Gulf of Maine (GOM) is a mid-latitude marginal sea that is bounded by the coastlines of New England and Atlantic Canada. Like other northern-hemisphere marginal seas, the general circulation of the GOM is cyclonic (Bigelow, 1927). The principal cyclonic circulation cell is centered in the eastern GOM and has accordingly sometimes been referred to as the Jordan Basin Gyre (e.g., Pettigrew et al., 1998). The schematic summer surface circulation diagram presented by

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[*] Corresponding author. Tel.: +207 581 4367; fax: +207 581 4332.
*E-mail address:* nealp@maine.edu (N.R. Pettigrew).

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Bigelow (1927) remained essentially unaltered until the study of Brooks (1985). Based primarily on hydrographic data, Brooks (1985) modified the schematic surface patterns, showing both the cyclonic flow of the interior regions and an indication of the coastal current system over the shelf regions that set southwestward along the coast of Maine. In addition, Brooks (1985) included an indication of the deep circulation patterns of the slope water, and its derivatives, that enter the Northeast Channel.

The relative isolation of the GOM from the open waters of the North Atlantic, together with significant input of fresh water from the Scotian Shelf (Smith, 1983; Brown and Irish, 1993) and several large river systems including the St. John, the Kennebec-Androscoggin, and the Penobscot, produce a degree of estuarine character to the general circulation and property distributions within the gulf. There is deep inflow of relatively high-salinity slope water through the Northeast Channel and compensating outflow of surface and intermediate waters through both the Northeast Channel and the Great South Channel at either end of Georges Bank. However, like other marginal seas but unlike archetypal estuaries, the GOM is large relative to its internal deformation radius (~10 km) and thus supports a vigorous meso-scale circulation including a complex, variable, and little-studied coastal current system that flows from the gulf coast of Nova Scotia to Massachusetts.

While little is known in detail about the Gulf of Maine Coastal Current (GMCC), it is generally thought to consist of multiple branches with at least partial and/or intermittent flow through from one to another (Lynch et al., 1997; Pettigrew et al., 1998). The GMCC has two principal branches: the Eastern Maine Coastal Current (EMCC), identified with the cold coastal band that extends from the mouth of the Bay of Fundy southwestward along the eastern coast of Maine to the vicinity of Penobscot Bay; and the Western Maine Coastal Current (WMCC), which extends from Penobscot Bay to Cape Cod Massachusetts, and is not easily identified by surface temperature patterns. The scientific consensus is that a major portion of the EMCC turns offshore at a variable location in the vicinity of Penobscot Bay (Brooks and Townsend, 1989; Bisagni et al., 1996; Pettigrew et al., 1998), contributing to the cyclonic circulation around Jordan Basin, and that another portion may continue southwestward contributing the WMCC (Pettigrew et al., 1998). The nature of the connection between the two principal branches of the GMCC, and the issue of whether or not there are times when the EMCC follows exclusively one route or the other, has remained unresolved.

The physical characteristics of the GMCC system have been the subject of intense interest but little direct observation. Most of the observations that have been reported from the shelf regions were part of larger-scale, sparsely sampled surveys that were focused on the overall circulation and water property distributions of the GOM (e.g., Bumpus and Lauzier 1965; Brooks, 1985; Brooks and Townsend, 1989; Pettigrew et al., 1998). Exceptions to this generalization are recent studies of the WMCC by Geyer et al. (2004) and Churchill et al. (2005) that incorporate modern current meter and hydrographic surveys.

Townsend et al. (1987) and Brooks and Townsend (1989) emphasize the importance of the coastal current system and its rich load of inorganic nutrients to the biological productivity of the GOM. Advective transport of the high-nutrient waters of the cold, vertically mixed, EMCC waters toward the southwest and offshore into the Jordan Basin was shown by Pettigrew et al. (1998) to represent significant contributions, especially to the offshore regions that are normally nutrient depleted during the late spring and summer.

The variability and pathways of the EMCC, and its connection to the WMCC, take on added importance given the very high densities of the toxic red tide dinoflagellate, *Alexandrium fundyense*,[1] that have been recently documented in the waters of the EMCC during summer (Townsend et al., 2001). The Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) GOM study showed that the concentrations of the red tide organism were consistently high during the summer months. Satellite data suggest that interannual differences in frontal zone structure associated with the EMCC are linked to the strength of toxic events along the western GOM shore (Luerssen et al., 2005). Thus the trajectories and pathways of the HAB-laden waters of the EMCC, which are centered on the outer eastern shelf away from the

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[1] Both *A. tamarense* and *A. fundyense* occur in the Gulf of Maine (Anderson et al., 1994). We consider these to be varieties of the same species (Anderson et al., 1994; Scholin et al., 1995). Thus, for the purpose of this study, the name *A. fundyense* is used to refer to both forms, as this is the dominant variety observed in the study area (Anderson et al., 1994).

near-shore shellfish beds, may prove to be a key element in the initiation and timing of nearshore red tide outbreaks along both the eastern and western shores.

Below we present analyses of the first current meter arrays that provided simultaneous time series data at multiple locations within both the EMCC and WMCC regions. In addition, several years of high resolution summer hydrographic surveys of the eastern and western shelves are presented, and the issue of the flow continuity between the eastern and western shelf regions is addressed.

## 2. Data and methods

The data used in this analysis come primarily from the ECOHAB-GOM field programs that spanned the periods March–August 1998, March–August 2000, and June–August 2001. The first two field seasons included the most extensive set of physical measurements including extensive summer hydrographic surveys (Townsend et al., 2001), and a minimum of five oceanographic buoy moorings that measured vertical profiles of horizontal currents using a combination of Doppler current profilers and in situ current meters, temperature, and salinity at several depths, and wind speed and wind direction (select moorings). Meteorological information was also garnered from the NOAA C-Man stations at Mount Desert Rock (MDR) and Matinicus Island (MI) and from NOAA Buoy 44007 near Portland Head in Maine.

Important ancillary data were available from experiments in which the authors were involved before, during, and after the ECOHAB-GOM field operations. These data include drifters and hydrographic surveys from 1994 to 1996 Gulf of Maine Regional Marine Research Program (GOM RMRP) and moored current measurements from the Gulf of Maine Ocean Observing System (GoMOOS) from 2001 to present. Our analysis also made use of multiple daily satellite sea surface temperature (SST) images from NOAA satellites, which were received and processed at the University of Maine. Monthly composites were formed from all available images over the study period (~120 images per month). Monthly SST anomaly images were formed by subtracting the 19-year (1985–2003) climatological monthly composite from each monthly composite.

The most extensive hydrographic surveys were performed in June, July, and August of 1998. These months represent the time when the GOM is most severely impacted by blooms of the toxic dinoflagellate *A. fundyense* During the cruises, a Seabird Electronics 911 CTD was used to acquire hydrographic data that were averaged to 1-m vertical resolution. The survey area covered approximately $4 \times 10^4\,\text{km}^2$, with 215 stations arranged in 19 transects. Across shelf spatial resolution within transects averaged roughly 10 km and their alongshore separation averaged approximately 30-km.

Dates of all large-scale ECOHAB-GOM hydrographic surveys and dates and locations of GOM RMRP drifter releases are given in Table 1. The deployment periods and locations of all large-scale array moorings, along with the deployment depths of moored sensors, are listed in Table 2.

## 3. Results and discussion

### 3.1. Large-scale interior summer circulation from the GOM RMRP experiment

In April of 1994, 1995, and 1996, five drifters were deployed along a line from central to northeastern region Jordan Basin in the eastern GOM. The drifters were normally drogued at 40 m depth using a "holey sock." The drag ratio of the drogue to the surface float containing the ARGOS transmitter was slightly in excess of 401, so that the drifters were nearly independent of the drag due to winds and surface currents.

The combined drifter tracks for the 3 years, presented in Fig. 1, reflect the overall cyclonic circulation of the GOM, and the gyre-like circulations in the eastern GOM reminiscent of the summer surface circulation diagrams of Bigelow (1927) and Brooks (1985). However, these drifter tracks suggest that the summer circulation pattern of the eastern GOM may be better characterized by a linked pair of recirculating cyclonic gyres, one each over the Jordan and Georges Basins, rather than by a single gyre over Jordan Basin. It is important to note that the drifters used in this study tracked the flow of waters below the pycnocline rather than in the near-surface layer. However, the drifter trajectories reinforce the impression garnered from satellite-derived summer SST fields, that there is a significant degree of isolation between the waters of the eastern and western interior regions of the Gulf. The only significant evidence of significant exchange between the eastern and western GOM comes from the drifters that traveled in roughly 50-km wide band that had the shelf break

Table 1
(A) ECOHAB large-scale hydrographic cruises and dates. (B) GOM RMRP drifter releases, locations, drogue depths, and dates

| Cruise identity | Dates |
|---|---|
| (A) ECOHAB-GOM cruises, 1998–2000 | |
| ECOH0698 | Jun 6–16, 1998 |
| ECOH0798 | Jul 6–17, 1998 |
| ECOH0898 | Aug 6–16, 1998 |
| ECOH0500 | Apr 23–May 3, 2000 |
| ECOH0600 | Jun 5–15, 2000 |
| ECOH0701 | Jul 20–29, 2001 |

(B) GOM RMRP drifter releases, 1994–1996

| Drifter identity | Release position | Release date | Drogue depth (m) |
|---|---|---|---|
| *CRUISE: RMRP0494 Apr 25–30, 1994* | | | |
| 22502 | 44 16.1N, 67 22.2W | Apr 29, 1994 | 10 |
| 22503 | 44 28.1N, 67 16.8W | Apr 29, 1994 | 40 |
| 22504 | 43 57.0N, 67 30.0W | Apr 29, 1994 | 40 |
| 22505 | 43 33.4N, 67 39.9W | Apr 29, 1994 | 40 |
| 22506 | 44 16.1N, 67 22.2W | Apr 29, 1994 | 40 |
| *CRUISE: RMRP0495 Apr 2–2, 1995* | | | |
| 8176 | 43 18.0N, 67 32.2W | Apr 3, 1995 | 40 |
| 8177 | 43 33.0N, 67 40.2W | Apr 4, 1995 | 40 |
| 8589 | 42 50.7N, 67 50.5W | Apr 3, 1995 | 40 |
| 22507 | 43 09.5N, 67 23.4W | Apr 4, 1995 | 40 |
| 22940 | 43 49.3N, 67 33.1W | Apr 4, 1995 | 40 |
| *CRUISE: RMRP0596 May 9–15, 1996* | | | |
| 18213 | 44 27.9N, 67 17.0W | May 11, 1996 | 40 |
| 18214 | 42 55.0N, 67 14.1W | May 13, 1996 | 40 |
| 18215 | 43 56.7N, 67 30.2W | May 10, 1996 | 40 |
| 18216 | 43 32.9N, 67 40.0W | May 11, 1996 | 40 |
| *CRUISE: RMRP0896 Aug 6–10, 1996* | | | |
| 18212 | 44 16.0N, 67.27.1W | Aug 8, 1996 | 40 |

as its inner boundary. These drifters suggest that there was transport from the eastern to western GOM in the waters at the base of the pycnocline in 1994–1996. Since no drifters were deployed on the shelf in this study, nor did any advect over the shelf proper, the GMCC is not explicitly represented.

It is interesting to note that in both 1994 and 1995, a drifter from the northeastern Jordan Basin advected cyclonically around the periphery of the linked Jordan and Georges Basin gyres, and was finally entrained into the anti-cyclonic Georges Bank Gyre. These drifters, which came from a region that has been shown (Townsend et al., 2001) to contain high concentrations of *A. fundyense* throughout the summer season, reached the northeast peak of Georges Bank in approximately 30 days. These trajectories represent a potentially important pathway for *A. fundyense* to be rapidly advected from the EMCC to Georges Bank.

The double gyre pattern in the eastern GOM suggested by the drifters was consistent with geostrophic calculations from hydrographic surveys taken during the same period. Fig. 2A shows the dynamic height calculated from a survey in May, 1996. Also shown are arrows indicating the surface geostrophic currents relative to a 150-db reference level. The geostrophic vectors clearly illustrate the recirculation in the Georges Basin Gyre and partially resolve the linkage between the cyclonic gyres that occupy the basin of the eastern GOM. Fig. 2B shows the depth of the 34 psu isohaline that is often used as a threshold indicating the presence of slope water in the GOM (Bigelow, 1927; Brooks, 1985). This figure shows that the two cyclonic gyres are associated with two domes of dense slope water within the Jordan and Georges Basins, with a low in the slope water topography occurring over the Truxton Swell that separates the two basins.

Table 2
Tabulated mooring locations, waters depths, deployment periods, sensor types, and sensor depths

| Station | Position | Water depth (m) | Period of record | Mooring configuration (instrument depths) |
|---|---|---|---|---|
| 1998 | | | | |
| MD1 | 43 36.5N<br>69 52.2W | 85 | Mar 28–Aug 20 | Velocity: S4 (3 m); VMCM (5 m); VACM (27 m)<br>Temperature (1,5,27 m)<br>Salinity (1,27 m) |
| MD4 | 43 55.8N<br>68 19.5W | 119 | Jun 11–Nov 14 | Velocity: ADCP (8–108 at 2 m resolution)<br>Temperature (8,40 m)<br>Salinity (8,40 m) |
| MD5 | 44 00.6N<br>68 23.5W | 83 | May 9–Nov 14 | Velocity: ADCP (8–72 at 4 m resolution)<br>Temperature (8,40 m)<br>Salinity (8,40 m) |
| MD6 | 44 17.4N<br>67 40.0W | 99 | Apr 1–Aug 13 | Velocity: ADCP (8–88 at 4 m resolution)<br>Temperature (8,30 m)<br>Salinity (8,30 m) |
| MD7 | 44 21.4N<br>67 43.4W | 64 | Apr 1–Aug 13 | Velocity: ADCP (6–58 at 2 m resolution)<br>Temperature (8,30 m)<br>Salinity (8,30 m) |
| 2000 | | | | |
| MD1 | 43 36.7N<br>69 51.9W | 79 | Apr 24–Aug 12 | Velocity: S4 (1.5 m); VMCM (3.5 m); VACM (77 m);<br>ADCP (9–80 at 1 m resolution)<br>Temperature (0.5,3.5,51,77 m)<br>Salinity (0.5,51,77 m) |
| ME2 | 43 31.7N<br>69 18.0W | 131 | Apr 8–Aug 15 | Velocity: S4 (2 m); VMCM (4 m); VACM (88 m)<br>ADCP (9-80 at 1 m resolution)<br>Temperature (1,4,50,88 m)<br>Salinity (1,50,88 m) |
| ME3 | 43 42.0N<br>69 21.0W | 96 | Apr 8–Aug 15 | Velocity: S4 (1.5 m); VMCM (3.5 m); VACM (88 m)<br>Temperature (0.5,3.5,50,90.5 m)<br>Salinity (0.5,50,90.5 m) |
| ME4 | 43 45.3N<br>68 31.3W | 152 | Apr 8–Aug14 | Velocity: 3DACM (2 m); ADCP (10-106 at 4 m resolution)<br>Temperature (1,2,10,40 m)<br>Salinity (1,10,40 m) |
| ME5 | 43 53.9N<br>68 38.2W | 87 | Apr 8–Aug 14 | Winds (−2 m)<br>Velocity: 3DACM (2 m); ADCP (10-74 at 4 m resolution)<br>Temperature (1,2,10,40 m)<br>Salinity (1,10,40 m) |
| ME6 | 44 06.4N<br><br>68 06.0W | 96 | Apr 7–Aug 13 | Velocity: ADCP (10-86 at 4 m resolution)<br>Temperature (10,40 m)<br>Salinity (10,40 m) |

The drifter data provide an estimate of roughly 60 days for the characteristic time scale of recirculation in the eastern GOM. This recirculation time scale seems to apply for both the Jordan and Georges Basin gyres, and is insensitive to whether the drifter is in the gyre interior or on the outskirts. For those drifters that circulate cyclonically around the outside of the pair of linked gyres as well as those that travel anticyclonically around Georges Bank Gyre the time scale is only slightly longer; in the 60–90 day range.

A circulation schematic is presented in Fig. 3 for the vernal circulation in the upper 40 m of the GOM. This diagram incorporates the drifter and hydrographic survey data discussed above, and additional hydrographic data not shown here. The schematic also builds upon the previous circulation schematics presented by Bigelow (1927), Brooks (1985), Pettigrew and Hetland (1995), and Xue et al. (2000). The eastern and western interior regions of the GOM are relatively isolated from one another, whereas the waters of the shelf and shelf-break region enjoy a leaky and/or intermittent connection near the mouth of Penobscot Bay. The principal features of the overall cyclonic interior circulation are a pair of linked cyclonic gyres over the Jordan

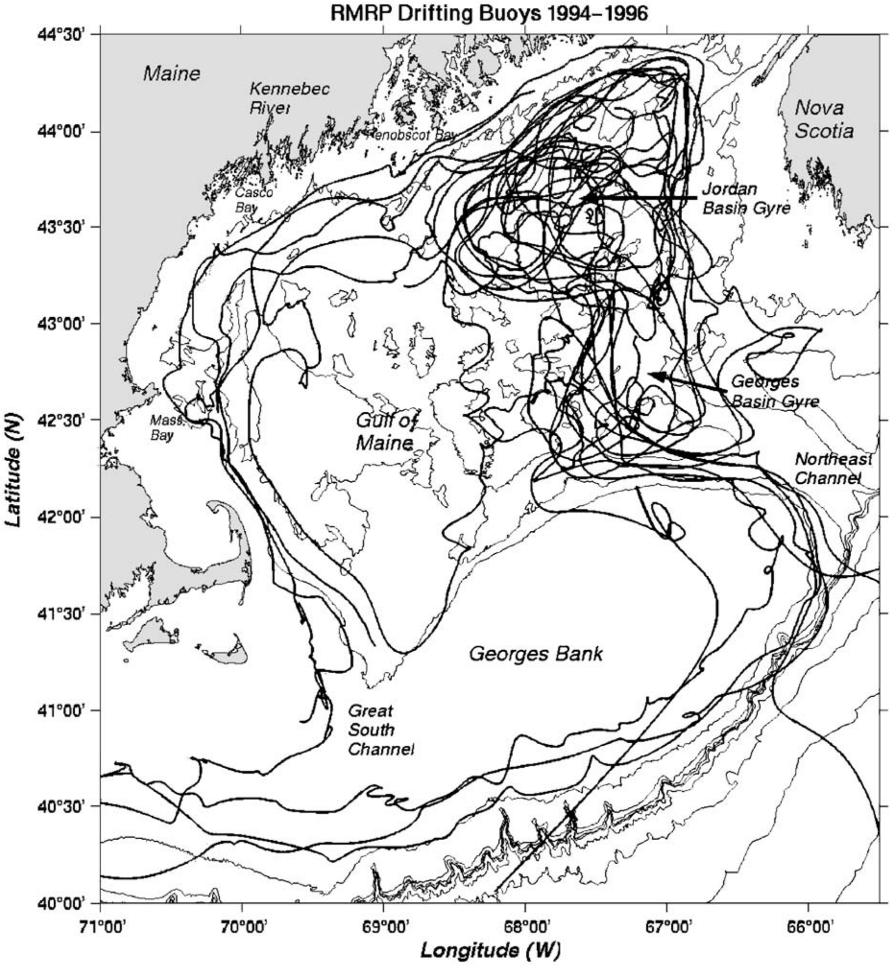

Fig. 1. Composite trajectories of satellite-tracked drifters released in the Jordan Basin in the eastern GOM in the spring seasons of 1994, 1995, and 1996. The drifters were drogued at 40 m, and thus mark the pathways of waters just beneath the seasonal pycnocline. Results emphasize two linked cyclonic gyres in the eastern GOM, and the lack of exchange between the eastern and western interior regions.

and Georges Basins. While the flow in the shelf regions are not adequately sampled by either the drifters or the geostrophic calculations of the GOM RMRP experiment, they are treated in detail below as the primary focus of the physical components of the ECOHAB-GOM experiment.

The chief uncertainty in Fig. 3 is the degree to which this (or any) schematic, can usefully represent a circulation system that is subject to seasonal and interannual variability that have yet to be meaningfully characterized. The other fundamental uncertainty in the schematic is nature of the circulation in the western interior of the GOM. Since the drifters were released in the eastern GOM and there is little east–west exchange in the interior, there is a paucity of drifter tracks in west. Thus it is the lack of information that visually suggests a lack of circulation in the western interior. On the other hand, hydrographic surveys tend to support the view that the circulation in the western interior GOM is weaker than that in the eastern interior.

### 3.2. 1998 moored current measurements

During the first ECOHAB-GOM field season, five moorings were maintained in the GMCC system throughout the spring and summer of 1998 (Fig. 4). Four shelf moorings were located east of Penobscot Bay within the EMCC, and one shelf mooring was deployed just east of Casco Bay in the WMCC. Although two additional moorings were

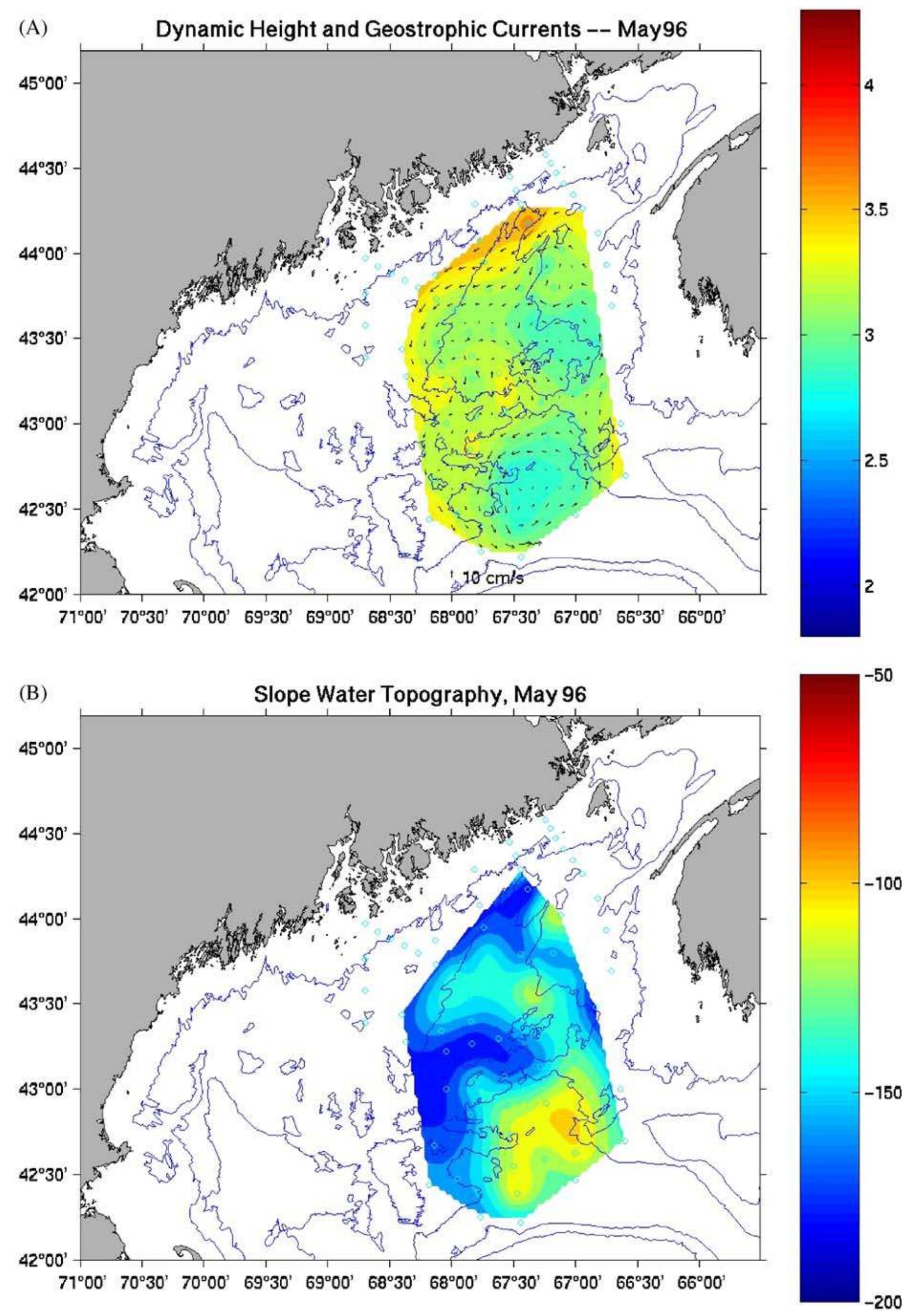

Fig. 2. (A) Dynamic height and surface geostrophic flow vectors from a survey of the eastern GOM in May 1996. The flow pattern shows clearly the Georges Basin Gyre along with indications of a stronger but more poorly resolved overall cyclonic circulation in the eastern GOM. Color coding gives dynamic height in dynamic cm. (B) Depth in meters of the 34 salinity isohaline showing two domes of slope water over the Jordan and Georges Basins.

deployed in the western nearshore during this deployment period, they were located within Casco Bay rather than the GMCC proper. An analysis of these nearshore records may be found in Janzen et al. (2005).

Monthly mean and variance statistics were calculated for 1998 moored current data that had been low-pass filtered with PL33 to remove the tidal and higher-frequency variability (Flagg, 1977). The statistics (not shown) indicate that the mean

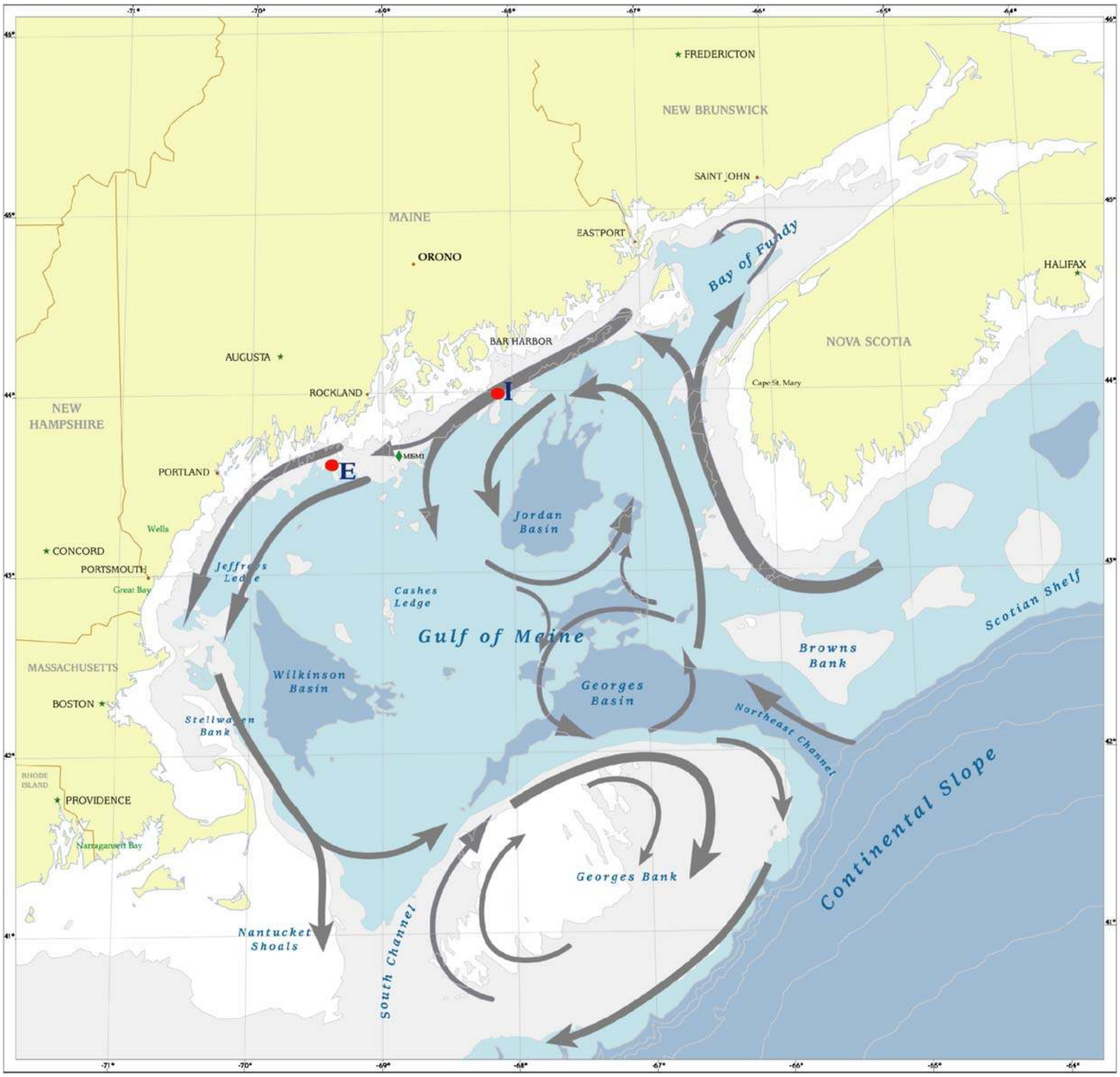

Fig. 3. Summer schematic circulation diagram of for the upper 40 m in the Gulf of Maine. The red dots marked E and I indicate the locations of real-time GoMOOS buoys that have been measuring currents since the summer of 2001.

currents are everywhere southwestward in opposition to the mean wind-stress forcing (not shown), and that the currents increase in the offshore direction. The flow on the eastern shelf (east of Penobscot Bay) is significantly stronger than that found on the western shelf, while the low-frequency variance is lower.

Fig. 5 shows the spatial distribution of mean flow vectors at 10 m for the four moorings east of Penobscot Bay, and at 5 m for mooring MD1 west of Penobscot Bay during June, 1998. Plots of mean currents throughout the water column show a qualitatively similar pattern, and individual monthly plots showed only minor variation through the summer season. The spatial variations of the mean flow depicted in this figure highlight the dominant feature of the GMCC during the summer of 1998: there appears to be a sharp contrast in the strengths of the southwestward mean flows on either side of Penobscot Bay. A strong alongshore convergence in the mean flow field would require an offshore redirection of the currents somewhere between

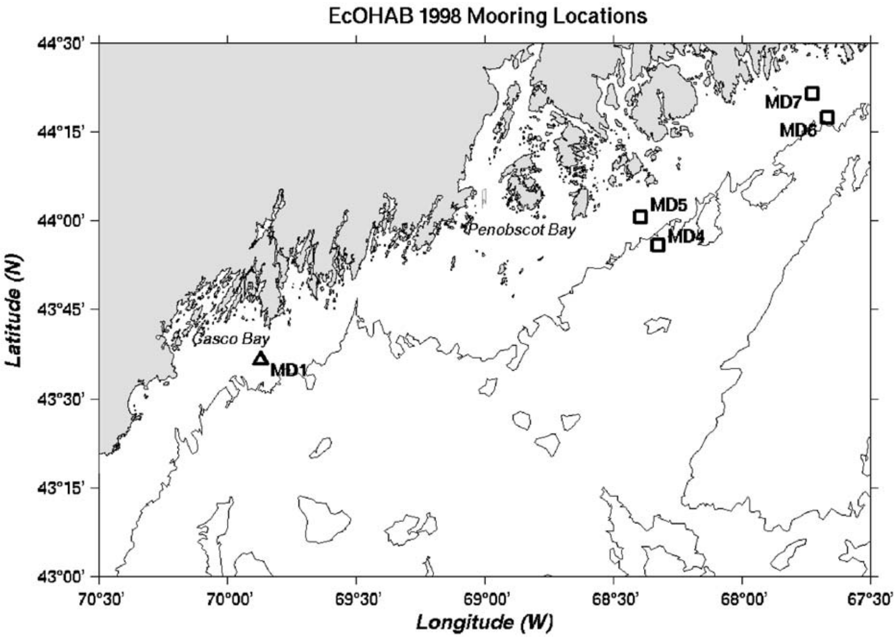

Fig. 4. Locations of current meter moorings for the summer of 1998. See Table 2 for deployment dates and instrument depths.

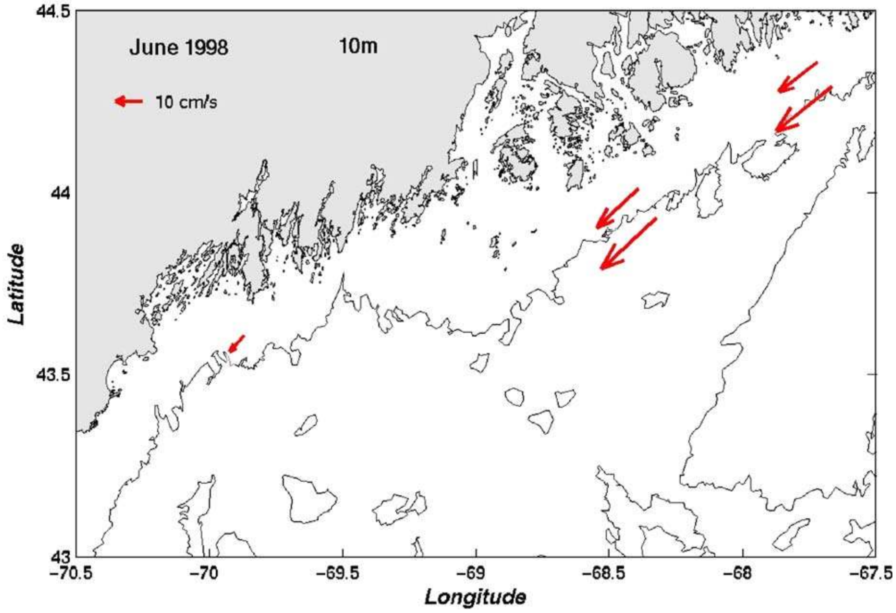

Fig. 5. Mean flow vectors for June 1998. The strong flows on the shelf east of Penobscot Bay are not evident west of the bay. The strong alongshore convergence implies an offshore veering of the EMCC in order to satisfy continuity.

MD4 and 5 and MD1 in order to satisfy continuity. Although a single mooring west of Penobscot Bay could have been poorly located to provide a reliable estimate of the transport in the WMCC, supporting data (below) confirm the transport discrepancy.

### 3.3. 1998 hydrographic surveys

The hydrographic surveys of June, July, and August covered the inner 100 km of the GOM from northern Massachusetts to the Bay of Fundy, and represent the most comprehensive hydrographic surveys ever performed in this region. The survey area covered approximately $4\times10^4\,\text{km}^2$ with 215 stations arranged in 19 transects. Across shelf spatial resolution within transects averaged roughly 10 km, and their alongshore separation averaged approximately 30 km. The three surveys were carried out during the months in which the GOM is most significantly impacted by blooms of the toxic dinoflagellate *A. fundyense*.

Computed dynamic heights and associated geostrophic currents for June 1998 (Fig. 6) clearly show that the bulk of the near-surface waters of the EMCC turned offshore east of Penobscot bay and separated from the shelf during the summer of 1998. The geostrophic currents also show that the flow regime undergoes a relatively abrupt transition to weak and less organized flow in the WMCC region west of Penobscot Bay. This flow discontinuity between the eastern and western shelf regions of the GOM contributes to the frequently observed dramatic discontinuity of the water properties between the eastern and western GOM (see Pettigrew et al., 1998). Dynamic-height fields for the July and August (not shown) were qualitatively similar although during July the offshore veering of the EMCC occurred on the order of 10 km west of Penobscot Bay.

The combination of the direct current measurements and the geostrophic calculations indicated that the bulk of the EMCC turned offshore in the vicinity of Penobscot Bay during the summer of 1998 and that there was little leakage from the eastern mid and outer shelf into the waters of the western shelf. The significance of this offshore retroflection of the current is that the transport discontinuity between the eastern and western shelf regions would tend to isolate the high concentrations of *A. fundyense* found in the waters of the EMCC in the summer of 1998 (Townsend et al., 2001) in the eastern GOM.

The hydrographic surveys of the ECOHAB program afford an opportunity to directly assess the degree of connectivity between of the EMCC and the WMCC through tracing of the coastal water masses. Moored current meter records from mid and outer shelf locations in 1998 broadly support the prevailing view that the bulk of the EMCC transport turns offshore in the vicinity of Penobscot Bay during the summer months. Hydrographic inventory of water masses characteristic of the core of the EMCC were used as a tracer to delineate the domain and pathways of these waters as they advect westward from the eastern Maine shelf into the transition zone.

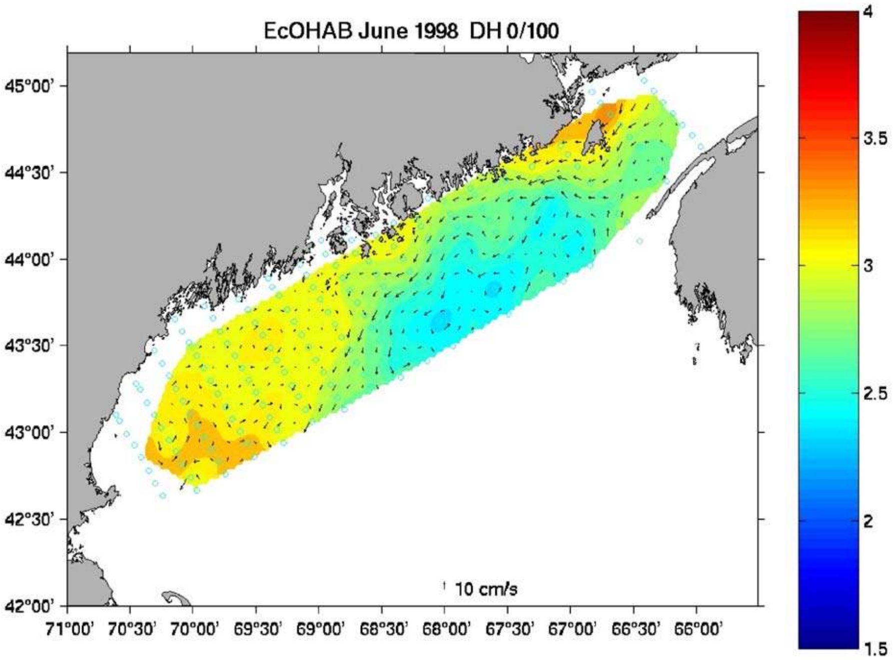

Fig. 6. Surface dynamic height contours and associated flow vectors for June 1998 relative to a 100-m reference level. Pattern shows clearly the offshore veering of the EMCC in the vicinity of Penobscot Bay.

The hydrographic properties of the core waters of the EMCC are generated by vigorous vertical mixing associated with the strong tidal currents characteristic of the shelf regions of the eastern GOM (Garrett et al., 1978)). The nearly complete vertical mixing of the northeastern Maine shelf (e.g., Pettigrew et al., 1998) makes this water a reliable tracer that can provide insight into the pathways of these waters, and delineate any leakage that may occur east to west from the EMCC to the WMCC.

The near-surface waters of the core of the EMCC in June 1998 had a salinity range of approximately 31.7–32.0 psu and an approximate temperature a range of 6.9–7.6 °C. To allow for solar heating of near-surface waters as they advected southwestward, we have allowed a total temperature range of 6.9–9.0 °C in delineating the spatial boundaries of the inventory of these EMCC core waters. Fig. 7 shows both the locations and the minimum depth of waters falling within this range of physical properties in the June 1998 survey. The visually striking feature of Fig. 7 is that, with the exception of two isolated subsurface stations in the western GOM, the water properties of the near-surface core of the EMCC are limited to the eastern GOM reflecting an isolation between the eastern and western GOM indicating that the core waters of the EMCC did not penetrate into the western GOM. East–west isolation in surface properties of the interior GOM has been previously noted by Pettigrew et al. (1998) and Thomas et al. (2003).

The color coding of the dots in Fig. 7 indicates the minimum depth at which the EMCC core water mass is found. The data show clearly that the EMCC core water mass is capped by surface waters along the edges of the EMCC and near its western extreme near the mouth of Penobscot Bay. These data are consistent with a kinematic description of the flow of the EMCC core subducting beneath less-dense waters from fresh-water runoff and the beneath less-dense surface waters offshore in Jordan Basin. The interpretation is that essentially all the EMCC core water mass is contained within the EMCC throughout the pycnocline layer of the

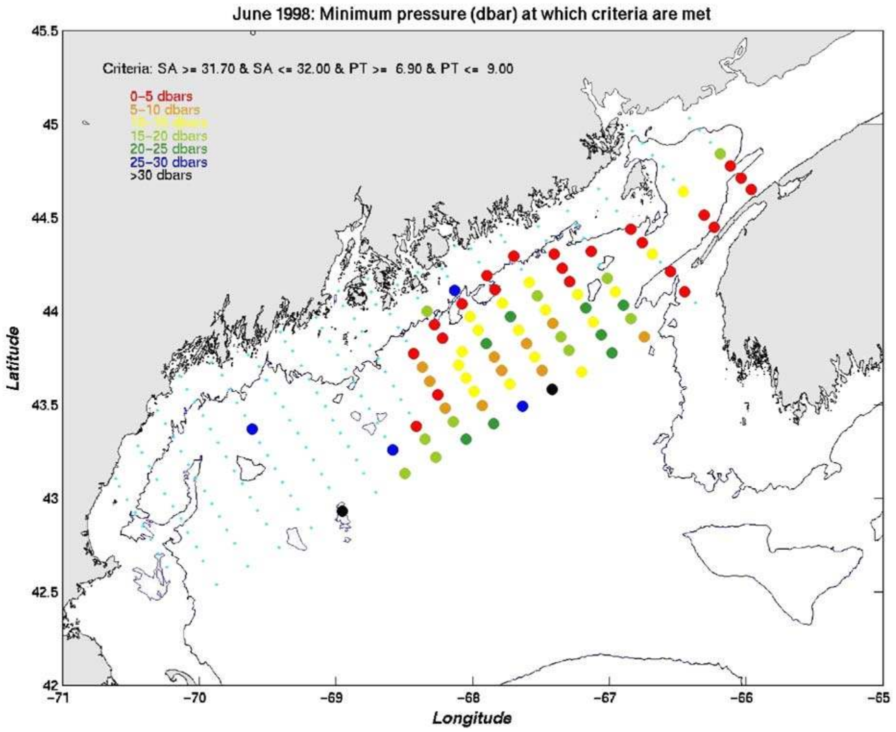

Fig. 7. Hydrographic inventory of EMCC core water characteristics for June 1998. The water mass is defined as having a salinity between 31.7 and 32 psu and a temperature between 6.9 and 9.0 °C. Colored dots show locations of stations at which water of these characteristics is found, and the color indicates the minimum depth of observation. The data show that with one exception, the waters making up the near-surface core of the EMCC are not found west of Penobscot Bay. The inventory shows also that the core waters properties are restricted to the pycnocline depths offshore of the EMCC.

eastern GOM, and none escapes to the western GOM except, potentially, through mixing.

The core of the EMCC is seen from moored current measurements, satellite SST distributions, and hydrographic surveys (Pettigrew et al., 1998; Townsend et al., 2001) to be most often centered on the middle-to-outer shelf near the 100 m isobath. Inshore of the core of this current, nearer to the 50 m isobath, is an inner boundary layer that is characterized by a water mass freshened by local runoff, including streams and non-point sources, and slowed by frictional effects. An inventory of the nearshore water mass in June 1998 is presented in Fig. 8. As in the case of the EMCC core waters, the distribution of this water is such that it is found at the surface only in the inner shelf regions east of Penobscot Bay. However, unlike the EMCC core water properties, the inner shelf waters properties are found in the western GOM, although they are found neither on the shelf nor at the surface, but rather in the pycnocline of the Wilkinson Basin. Thus, although there appears to be a marked discontinuity in surface transport and hydrographic properties between the surface waters of the eastern and western GOM shelf, the surface waters of eastern inner shelf may gain subsurface entry to the western interior GOM.

The hydrographic shelf-water inventories indicate that the EMCC did not feed the WMCC during the summer of 1998. Thus, an alternate source for waters of the WMCC must be sought. Although much weaker than the EMCC in 1998, the flow near Casco Bay was southwestward with a depth-averaged mean on the order of 0.05 ms$^{-1}$. One potential source of the western coastal current is the buoyant outflow of Penobscot Bay driven ultimately by the Penobscot River. Fig. 9 shows a hydrographic inventory of the river-freshened surface waters of outer Penobscot Bay. This hydrographic distribution shows that the water properties seen near the surface in Penobscot Bay are also found in Jericho and Blue Hill Bays to the east, and in the

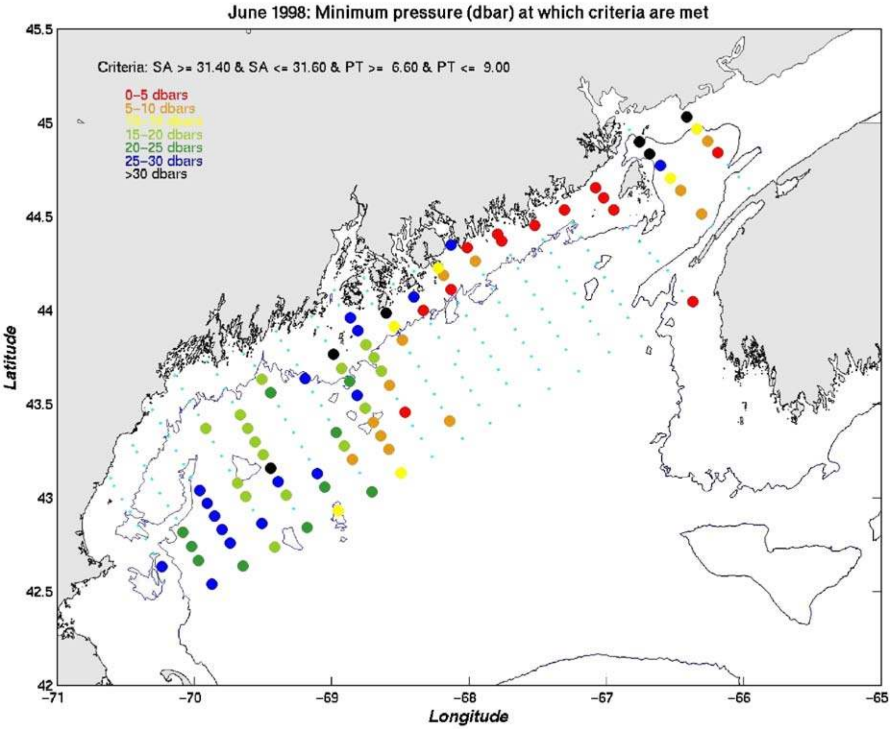

Fig. 8. Hydrographic inventory of inner shelf EMCC water characteristics for June 1998. The water mass is defined as having a salinity between 31.4 and 31.6 psu and a temperature between 6.6 and 9.0 °C. Colored dots show locations of stations at which water of these characteristics is found, and the color indicates the minimum depth of observation. The data show that while the inner shelf EMCC waters are exported to west of Penobscot Bay they are found subsurface and offshore from the vicinity of Penobscot Bay westward. Thus, although the inner shelf waters may be found in the pycnocline waters of the interior western GOM, they do not become part of the WMCC shelf flow.

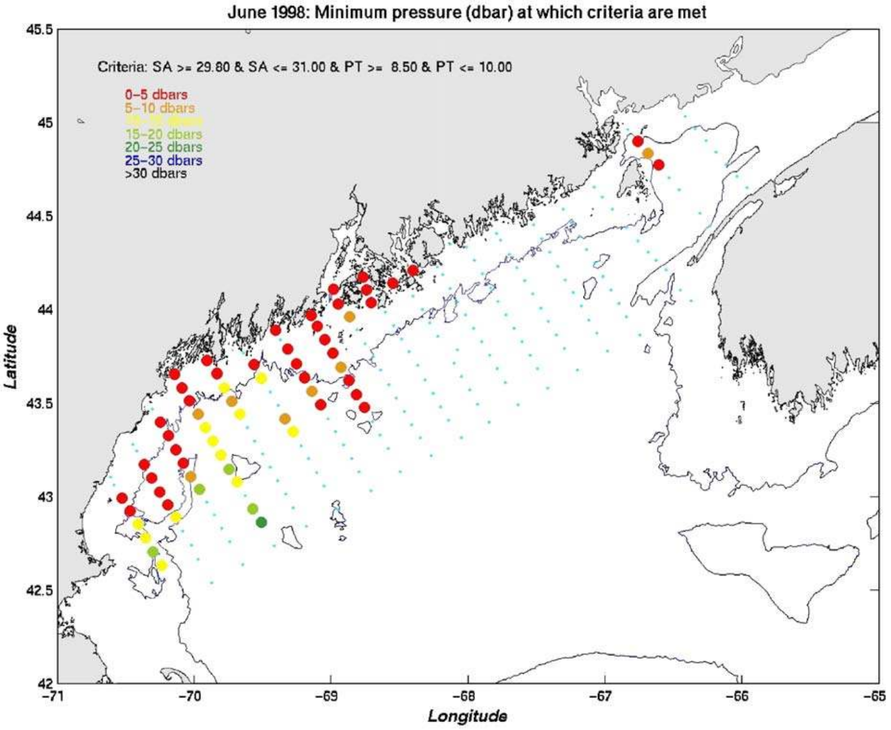

Fig. 9. Hydrographic inventory of water characteristics defined as those of the Penobscot Bay near-surface outflow for June 1998. The water mass is defined as having a salinity between 29.8 and 31 psu and a temperature between 8.5 and 10.0 °C. Colored dots show locations of stations at which water of these characteristics are found, and the color indicates the minimum depth of observation. The data show that the coastal outflows emanating form bay just west of the EMCC turnoff are found throughout the near-surface waters of the WMCC and the upper pycnocline waters just seaward of the shelf break. The water property distribution suggests that the WMCC has its headwaters in the Penobscot Bay outflow. West of Casco Bay the Penobscot waters, while still at the surface, are found on the outer shelf and beyond, suggesting that they may have been displaced by fresher outflows from the Kennebec, Saco, and Merrimac rivers.

near-surface shelf waters to the westward extent of the survey region, i.e. off Cape Ann, Massachusetts. However, these water properties are absent at the innermost stations in the western end of the survey, suggesting that the Kennebec, Saco, and/or Merrimac Rivers may contribute yet another boundary layer on the western inner shelf. Thus the kinematic structure of the coastal current system can be characterized by buoyant water masses from a series of river systems that sequentially displace the inner shelf waters offshore and are in turn displaced farther downstream. In the case of the Penobscot outflow the entire body of the core of the EMCC is deflected offshore and the alongshore transport is interrupted. These interpretations are consistent with the numerical model presented by Brooks (1994).

Hydrographic inventories of the EMCC core, inner shelf, and Penobscot Bay surface waters for the months of July and August 1998 yield very similar results. Although the temperature and salinity ranges characterizing the region evolve over the summer season, the spatial patterns remain essentially unaltered. The core waters of the EMCC remain sequestered in the eastern GOM throughout the summer season, the inner shelf EMCC waters subduct and move offshore after passing Penobscot Bay, and the surface water properties of the Penobscot Bay Estuary are also found westward throughout the entirety of the western GOM shelf region during the summer.

The combination of the moored current meter data that show a large discrepancy in volume transport and the coastal water mass inventories of the summer of 1998 suggest that there is little direct transport of the Alexandrium-laden EMCC water (Townsend et al., 2001) beyond Penobscot Bay. Those waters that do spread beyond the EMCC region seem to subduct and might be expected to result in subsurface populations of the toxic dinoflagellate as was observed by Townsend et al. (2001).

### 3.4. 2000 moored current measurements

The second major field deployment of the ECOHAB-GOM program (2000) concentrated on retroflection and frontal region near Penobscot Bay. Six current meter moorings were deployed (Fig. 10). Moorings MD1 and ME6 were intended to monitor (respectively) the WMCC and EMCC far from the more complex retroflection/frontal region, and moorings ME2–ME5 were placed on either side of the frontal region.

The summer mean flow vectors shown in Fig. 11 make clear the extreme differences between the summer flow regimes of 1998 and 2000. In the summer of 2000 the discrepancy between the southwestward transports in the GMCC east and west of Penobscot Bay was dramatically reduced compared to 1998. This reduced transport discrepancy was produced both by an increase in the current strength west of Penobscot Bay and a decrease current strength east of Penobscot Bay. The result of these changes is that the major alongshore flow convergence noted in 1998 is not in evidence. The lack of the strongly convergent alongshore flow obviates the need for a major offshore veering of currents in order to satisfy continuity. The pattern of the mean flow vectors in fact suggests that much of the flow from the EMCC continued on to feed the WMCC during the June 2000.

### 3.5. 2000 hydrographic surveys

In 2000 only two hydrographic cruises were undertaken. The first cruise was in late April through early May and the second in June (see Table 1). Thus direct comparison of hydrographic conditions in 1998 and 2000 is possible only for the month of June. The hydrographic stations for the June 2000 were relatively sparse, and did not extend as far into the western GOM. Fig. 12 shows a dynamic height calculation and the associated geostrophic currents for June 2000. In comparison to the results for June 1998, the calculated geostrophic currents are weaker and show few east–west differences. The dynamic height field suggests that the GMCC in 2000 is generally a continuous current without the characteristic offshore veering and alongshore discontinuity between the EMCC and the WMCC that characterized the summer of 1998, and that has been frequently reported for other years (Brooks and Townsend, 1989; Lynch et al., 1997; Bisagni et al., 1996; Pettigrew et al., 1998). The continuous band of coastal flow indicated by the geostrophic vectors is consistent with the mean current vectors directly

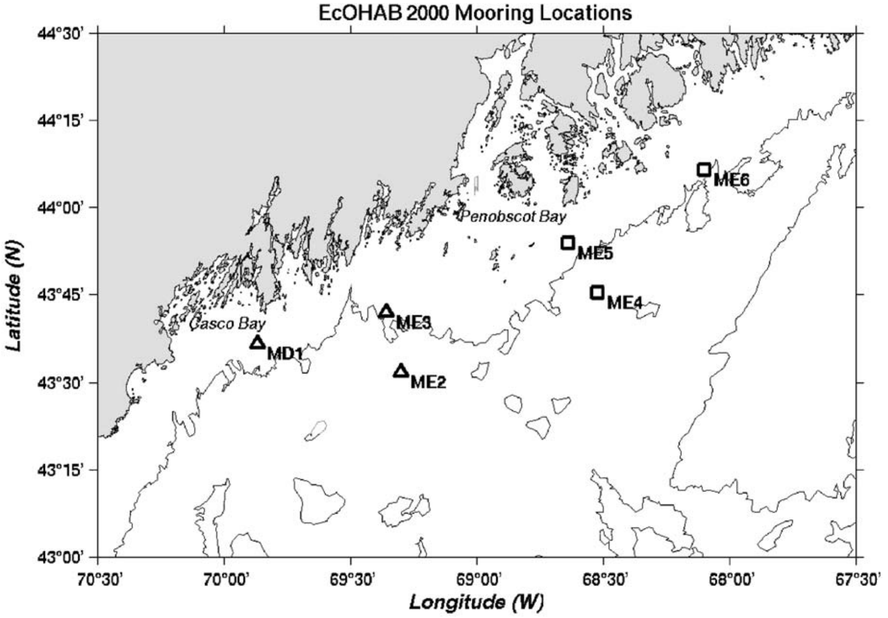

Fig. 10. Location of current meter moorings for spring and summer 2000.

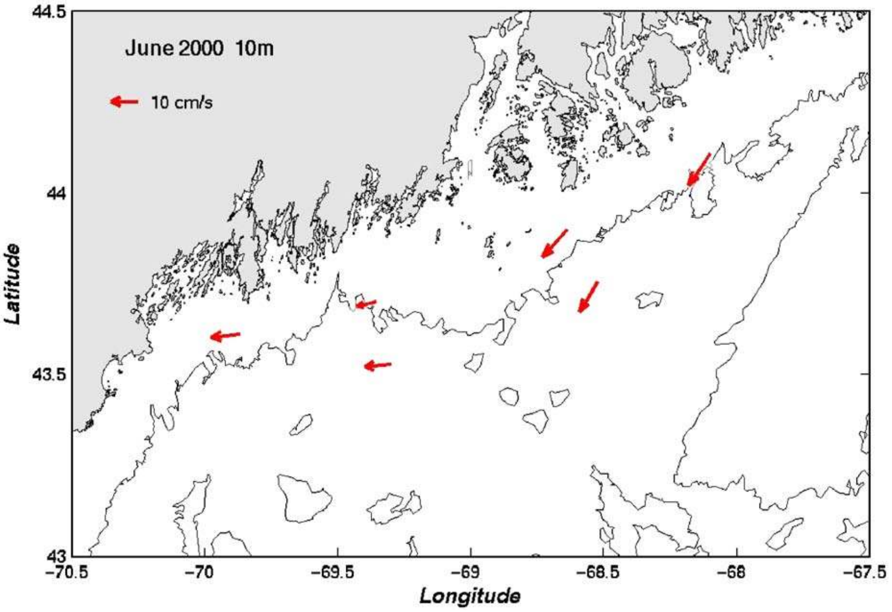

Fig. 11. Mean flow vectors for June 2000. Some evidence of offshore veering is observed east of Penobscot Bay, but the strength of flow in the surface WMCC is essentially the same as that in the EMCC. This transport equivalence argues against a disruption of the near surface southwestward flow as occurred in 1998. Compared to 1998, the mean flows in the EMCC have decreased by roughly half and the WMCC approximately doubled, resulting in approximately balanced surface transports in the EMCC and WMCC in 2000.

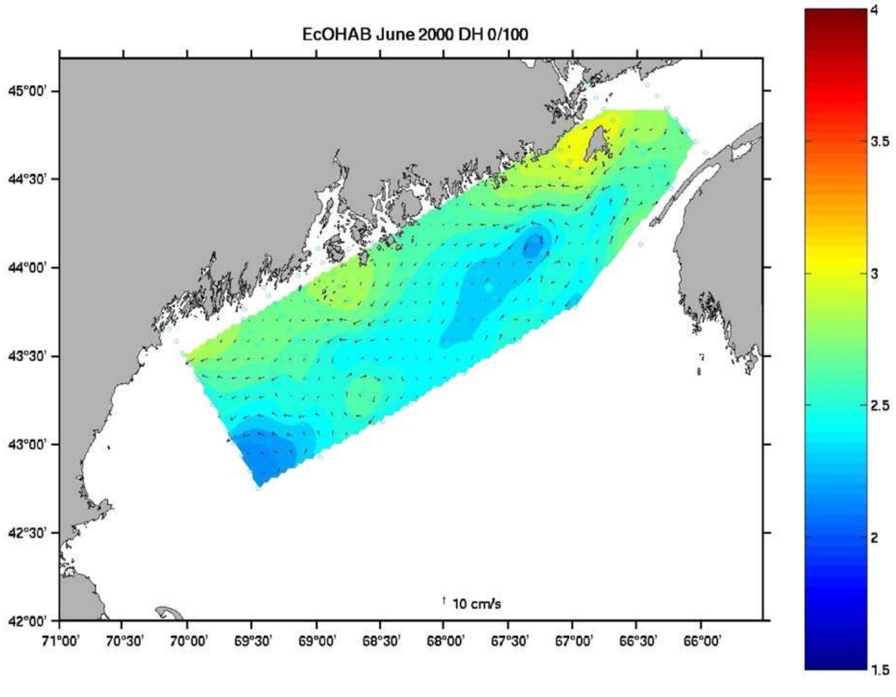

Fig. 12. Surface dynamic height contours and associated flow vectors for June 2000 relative to a 100-m reference level. Patterns show a deflection near Penobscot Bay, but no disruption of the westward transport that was seen clearly in June 1998.

observed by the current meter moorings, which suggests no major alongshore flow interruption in the vicinity of Penobscot Bay.

A comparison of the deep offshore waters found in the summers of 1998 and 2000 shows that the slope waters in 2000 were significantly warmer, saltier, and denser in 2000 than in 1998. In addition, there was considerably less contrast between the eastern and western Gulf in terms of the depth at which the slope water was found. These differences in deep density distribution were reflected in the contrast if the geostrophic currents calculated for the summer seasons of 1998 and 2000.

Shelf-waters were inventoried for June 2000 as they were in 1998. Although eastern Maine waters were significantly warmer and saltier in 2000 than in 1998 (both near the surface and at depth), near-surface water masses were defined for the core of the EMCC, the EMCC inner shelf waters, and the Penobscot Bay outflow, and their inventories are shown, respectively, in Figs. 13–15. The distributions of these water masses are very different than that observed in 1998, but one that is consistent with both the current meter data and the geostrophic calculations. In June 2000 the near-surface waters of the EMCC core were not sequestered in the eastern GOM, but rather were found as far westward as Casco Bay, which was the western extreme of the June 2000 survey. While the EMCC core water properties were found west of Penobscot Bay, there was still a tendency for the distribution to be subsurface from the mouth of Penobscot Bay westward. Inner shelf waters and waters of Penobscot bay origin were both in evidence on the western shelf, although once again they tended to be absent from the surface layer. The water mass distributions add to the notion that in June 2000, in marked contrast to June 1998, the EMCC flowed westward beyond Penobscot with little abatement of the alongshore transport.

### 3.6. 2001 hydrographic survey

In July 2001 a large-scale hydrographic survey had coverage similar to the surveys of 1998 and 2000. The dynamic-height contours and geostrophic velocity vectors for this survey are shown in Fig. 16. The dynamic height and flow vector distributions in

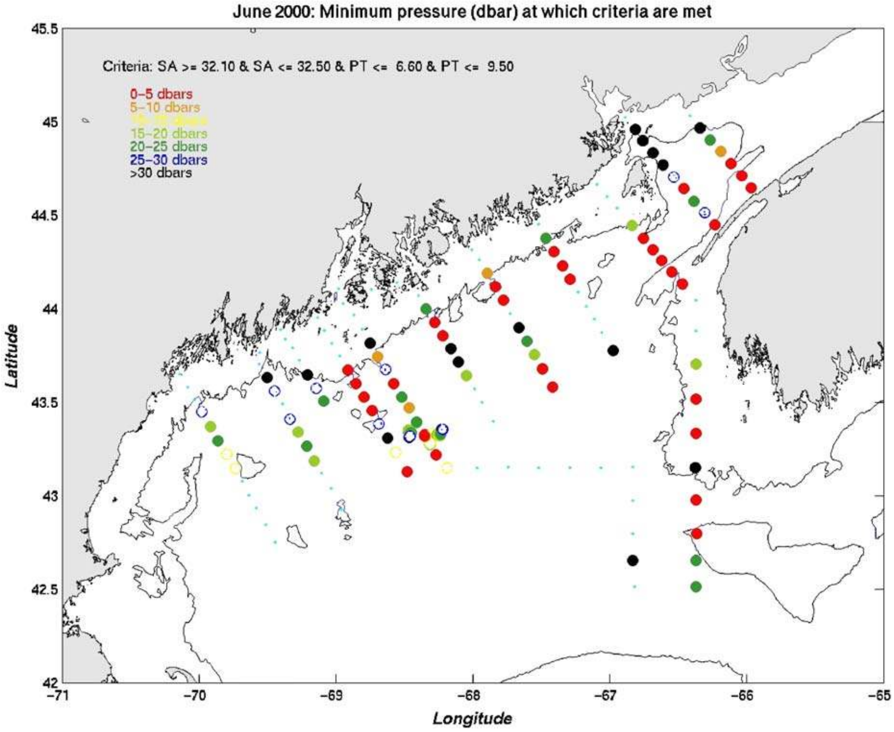

Fig. 13. Hydrographic inventory of EMCC core water characteristics for June 2000. The water mass is defined as having a salinity between 32.1 and 32.50 psu (significantly more saline than in 1998), and a temperature between 6.6 and 9.5 °C. Colored dots show locations of stations at which water of these characteristics is found, and the color indicates the minimum depth of observation. The data suggest that the waters characterizing the near-surface core of the EMCC are found all the way to the westward end of the survey region. There is a slight offshore deflection at the mouth of Penobscot Bay and possible subduction of the waters that extend westward and offshore.

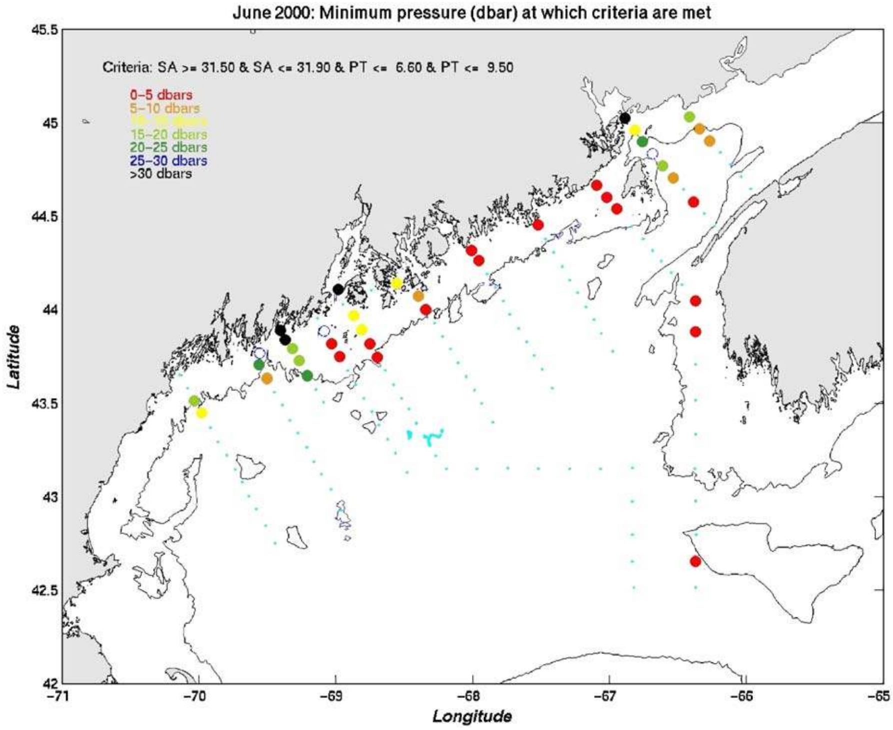

Fig. 14. Hydrographic inventory of EMCC inner-shelf water characteristics for June 2000. The water mass is defined as having a salinity between 31.5 and 31.90 psu (slightly more saline than in 1998), and a temperature between 6.6 and 9.5 °C. Colored dots show locations of stations at which water of these characteristics is found, and the color indicates the minimum depth of observation. The data suggest that the waters making up the near-surface inner portion of the EMCC are found all the way to the westward end of the survey region but that there may be subduction west of the mouth of Penobscot Bay and migration to the outer shelf west of the Kennebec River and Casco Bay.

the vicinity of Penobscot Bay show a case intermediate to the extremes of virtually no through flow in the summer of 1998 and nearly unrestricted through flow in summer 2000. In July of 2001, the geostrophic flow pattern shows a large proportion of the EMCC turning offshore east of Penobscot Bay, but also suggests significant leakage of the inner eastern shelf transport beyond the bay onto the western shelf.

Keafer et al. (2005) carried out a careful examination of the 2001 hydrographic data set. In their analysis they conceptually separated the westward geostrophic flow observed in the eastern GOM during the spring and summer of 2001 into an “inside” and an “outside” track. The inside track was a buoyancy-driven flow that contained most of the *A. fundyense* cells observed in the surveys and appeared to move continuously along the coast in a nearshore band from the eastern to the western GOM. The outside track was the high-velocity core waters of the EMCC and was deflected into the interior Gulf along the western margin of Jordan Basin.

### 3.7. SST anomalies

The contrast in subsurface physical properties, and their three-dimensional distributions, that were evident in the forgoing hydrographic inventories suggest markedly different connectivity between the EMCC and WMCC in the summers of 1998 and 2000, with 2001 an intermediate case. Satellite SST patterns during the summers of 1998, 2000, and 2001 also highlight the differences between these 3 years. The SST anomalies for 1998, 2000, and 2001 were calculated relative to a 19-year mean (1985–2003) for July and are presented in Fig. 17. The SST anomalies show that the western GOM and WMCC region were warmer than normal climatology in 1998, significantly colder in 2000, and mixed in 2001. These patterns are consistent with the preponderance of data that suggest very restricted through flow from the cold EMCC in summer 1998, nearly unrestricted through flow in summer 2000, and through flow only from the inner shelf in 2001. In each case the through flow of

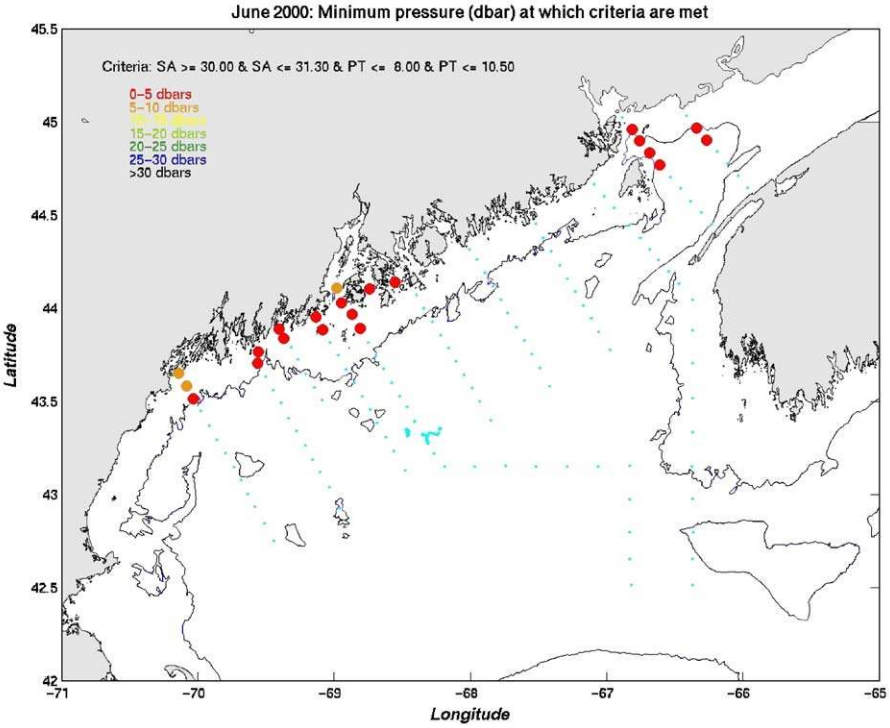

Fig. 15. Hydrographic inventory of Penobscot Bay outflow water characteristics for June 2000. The water mass is defined as having a salinity between 30.0 and 31.30 psu (significantly more saline than in 1998), and a temperature between 8.0 and 10.5 °C. Colored dots show locations of stations at which water of these characteristics is found, and the color indicates the minimum depth of observation. The data suggest that the waters making up the near-surface core of the outflow of Penobscot Bay feed the WMCC as in 1998.

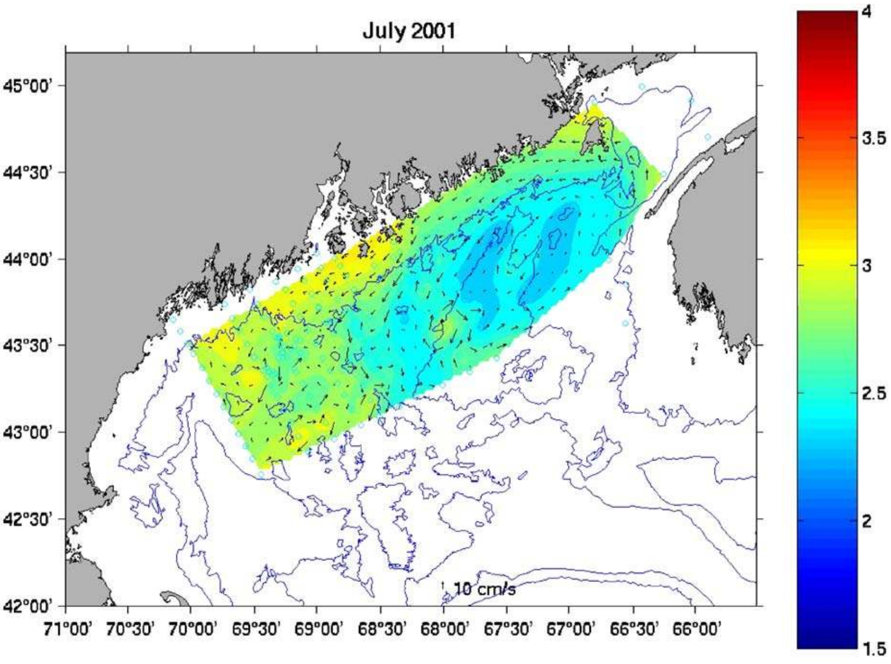

Fig. 16. Dynamic height and geostrophic velocity vectors for the July 2001 survey. The summer of 2001 apparently represents a case intermediate between the 1998 and 2000 extremes. While the bulk of the EMCC turns offshore east of Penobscot Bay as in the summer of 1998, there is significant leakage of mid and inner shelf flows past the Bay into the WMCC region.

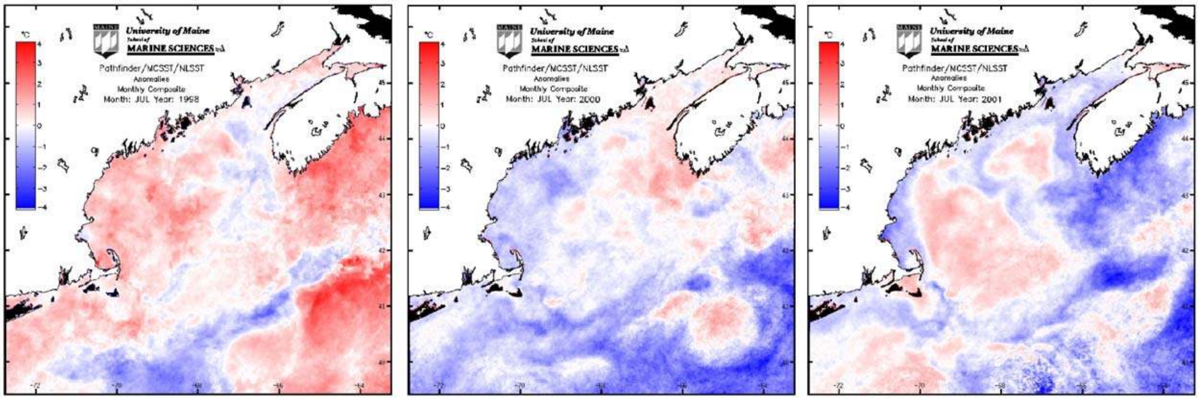

Fig. 17. Monthly composite images of SST anomalies calculated relative to a 19-year (1985–2003) July mean for 1998 (left), 2000 (middle), and 2001 (right). Red shading indicates warm anomalies and blue represents cold anomalies relative to the 19-year mean. Anomaly patterns show that conditions in the WMCC and the western GOM are significantly warmer than average in 1998 (left) significantly colder than average in 2000 (middle), and mixed in 2001 with the inner shelf cold and the offshore warm. These images are consistent with low EMCC impact west of Penobscot Bay in 1998 (gate closed), high EMCC impact into the western region in 2000 (gate open), and high impact nearshore and low impact offshore in 2001 (gate ajar).

EMCC water results in cold anomalies in the western GOM. Of particular interest is the anomaly field for July 2001. The cold signatures of both the intrusion of the EMCC inner shelf waters (inner track) beyond Penobscot Bay, and the offshore veering of the EMCC core (outer track) are clearly visible.

### 3.8. Long-term current measurements east and west of Penobscot Bay

Since the summer of 2001 the University of Maine has maintained real-time buoys distributed throughout the GOM as part of the GoMOOS. Two of the GoMOOS moorings (E and I in Fig. 3) are well positioned to monitor the alongshore convergence associated with the veering of the EMCC near Penobscot Bay. Monthly average current speed and direction at 2 m depth are plotted in Fig. 18 for the period July 2001 through October 2004. These current records show that every summer since 2001 the current speed in the EMCC (buoy I) exceeds that observed in the WMCC (buoy E) by 50–75%. Thus conditions during the intensive field seasons of the ECOHAB-GOM (1998 and 2000) probably represent opposite extremes in terms of the degree of flow continuity between the EMCC and WMCC during summer.

These GoMOOS records represent the first long-term direct current measurements capable of showing the marked seasonality of the GMCC. Of particular interest is the observation that the transport discrepancy between the EMCC and the WMCC appears to be a highly seasonal feature. During the fall and winter seasons the upper-layer transports in the EMCC and WMCC are roughly equal. In the spring, currents in both regions accelerate with the spring freshet, but the EMCC current at 2 m depth increases much more substantially giving rise to the alongshore convergence between buoys E and I. The seasonal flow convergence suggests that the associated offshore veering of the EMCC arises in the spring, persists throughout the summer, and then diminishes during the fall.

Doppler current profiler records show that seasonal alongshore convergences also occur between the locations of buoys E and I in the near-surface and pycnocline layers, and that they are in phase with the near-surface convergences. However, below 50 m depth the GMCC shows a significantly different seasonality. Doppler currents for the 4-m bin centered at 74 m depth show that the seasonal variation of the high flow and high alongshore convergence in the lower water column is out of phase with that of the surface layers (Fig. 19). Thus it appears that the deep EMCC may veer offshore during winter while the upper water column flows through toward the southwest. The reason for this behavior is likely found in the seasonality of the alongshore baroclinic pressure gradient. The crux of the argument is that the sign of the density differences between the deep waters of the WMCC and EMCC reverse seasonally and are out of phase with the seasonally reversing density difference in the

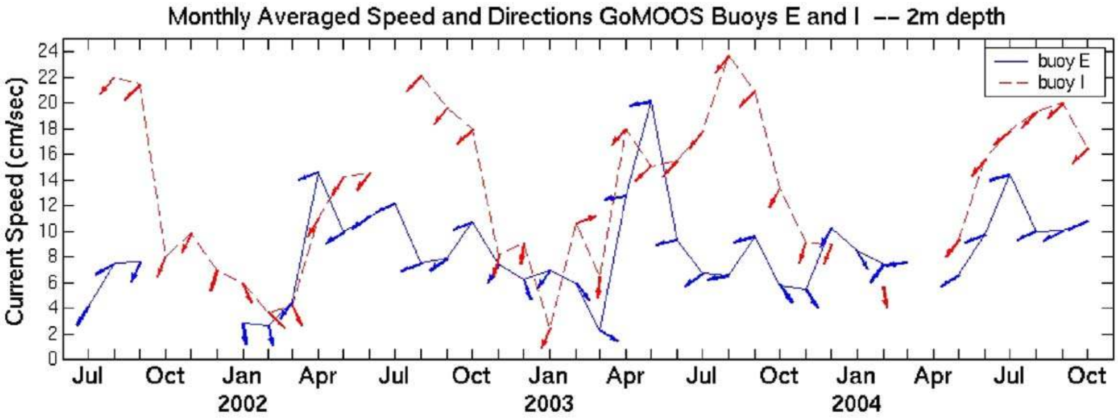

Fig. 18. Current speed and direction at GoMOOS Buoy I (EMCC) and Buoy E (WMCC) at 2 m depth from July 2001 to October 2004. The speed differences emerge in the late spring and disappear in the fall, suggesting that the offshore veering of the EMCC is a seasonal feature. It also suggests that the offshore veering observed in 1998 was typical of the summer circulation and that the through-flow observed in 2000 was anomalous. An unexpected feature of these current records is that both the EMCC and WMCC acquire an eastward component in late winter/early spring. In 2002 the EMCC underwent a true reversal with mean currents toward the northeast.

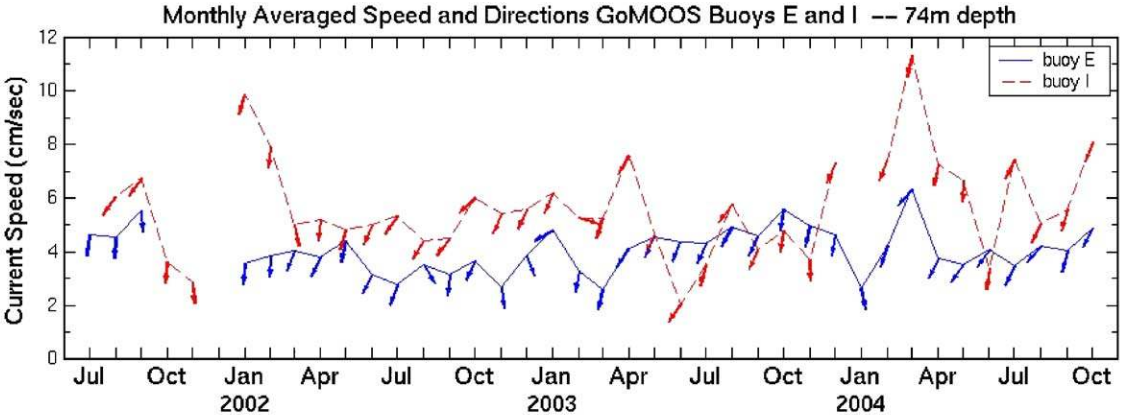

Fig. 19. Deep current speed and direction at GoMOOS Buoy I (EMCC) and Buoy E (WMCC) at 74 m depth from July 2001 to October 2004. The large speed differences emerge in the winter and decrease or disappear in late spring/summer, suggesting a seasonal offshore veering of the deep EMCC that is out of phase with the surface veering. The major EMCC surface reversal of 2002 (see Fig. 18) is seen to penetrate to the deep water.

upper water. That is, the deep EMCC waters, while denser than deep WMCC waters in summer, are less dense than deep WMCC waters during the winter (confirmed in GoMOOS 50-m temperature and conductivity records). Thus, the deep EMCC impinges on a relatively dense water mass between buoys E and I. The associated deep baroclinic pressure gradient force is northeastward in the transition region during the winter and is consistent with a geostrophic deep offshore flow. From the kinematic point of view the dense winter waters of the deep western shelf may be thought of as blocking the southwestward progress of the deep EMCC.

Another surprising feature of the winter GMCC kinematics is the consistent winter/early spring appearance of an eastward flow component in the monthly mean current records at both buoy E and I. An eastward component represents a “reversal” of the GMCC, although in most cases the weak currents are southeastward and are more offshore than up coast. However, on occasion, such as in February 2003, the EMCC current undergoes a true reversal, with average currents on the order of $0.1\,\mathrm{m\,s^{-1}}$ directed toward the northeast. Similar seasonal trends and the interannual differences of the GMCC were found in the model simulation of

Xue et al. (2005). These episodes are not well correlated with wind forcing. It is conceivable that these late-winter/early-spring flow episodes could have significant ecological implications. The slacking and/or reversals occur during the period of the annual early spring bloom when light levels become high enough to support vegetative cell division. The February–March period is also the time when the highest concentrations of benthic *A. fundyense* cysts are found suspended in the upper water column within the EMCC (Kirn et al., 2005). A GMCC weakening or reversal at this time may thus represent a retention mechanism through which cysts and early vegetative cells would not be swept southwestward or may even move upcoast for periods up to 30 days and distances up to 200 km. With this mechanism it becomes possible for a cyst bed to serve as the source or initiation of an *A. fundyense* bloom in a region that is climatologically upstream.

## 4. Summary and conclusions

The GMCC is a complex and intriguing coastal current system. It is characterized during spring and summer by remarkable contrasts in both flow properties and physical properties between its two principal branches, the EMCC and the WMCC. It is a coastal current system with a mean flow that opposes the mean wind stress throughout the spring and summer seasons.

The mean summer surface circulation in the GOM is cyclonic over the basins and as a whole. In the eastern GOM, there exists a pair of linked cyclonic gyres in Jordan and Georges Basins that tend to increase residence times in the east and limit the exchange between the upper waters of the eastern and western interior GOM. This isolation is manifest in the large summer differences SST and other water properties that are commonly observed to exist between the eastern and western Gulf.

The general circulation of the GMCC is subject to strong interannual, seasonal, and shorter-term variability, all of which may affect strongly the advective distribution of *A. fundyense* and other phytoplanktonic species. The data suggest that the degree of connectivity between the EMCC and WMCC is highly variable. Flow conditions observed in the summer of 1998 represent the "gate closed" condition, while summer of 2000 represents "gate open," and summer 2001 "gate ajar." These findings are consistent with the SST analysis of frontal zones over a 13-year period by Luerssen et al. (2005).

The hydrographic sections show that in 2000, the deep waters (~100 m) were significantly denser in both eastern and western GOM compared to 1998, and the east–west density differences were much reduced. The hydrographic distributions indicate an anomalously large transport of dense slope water into the GOM in 2000, and this large pool of water dense resulted in a broad-scale cyclonic circulation that over came the usual tendency for isolation of the eastern and western cyclonic circulation cells. Long-term current meter records from the GoMOOS program indicate that the typical summer condition is "gate ajar" in which most EMCC water is deflected offshore, but significant leakage occurs, especially in the nearshore region.

There appears to be little or no direct through flow of near-surface waters from the core of the EMCC to the WMCC in the summer of most years. The main body of the EMCC turns offshore near Penobscot Bay and may subduct beneath the less dense surface waters of the eastern interior basins. This lack of export of EMCC waters to the western GOM is of particular interest since the EMCC core often has high concentrations of the toxic dinoflagellate *A. fundyense.* A subductive process is one potential explanation of the subsurface *A. fundyense* maxima reported by Townsend et al. (2001) along the edges of the EMCC core. The inventory of eastern inner shelf water properties are consistent with the notion that these waters are subducted into the pycnocline as they flow southwestward, and are exported to the Wilkinson Basin in the western GOM. While they may contain moderate levels of *A. fundyense*, they tend drift off shelf and would not likely come in contact with the shellfish beds of the western gulf. However, it is unknown if *A. fundyense* would act as a passive particle or may swim to the surface and be transported shoreward by other mechanisms.

Under normal summer conditions the surface waters of the WMCC appear to originate in the outflow from Penobscot Bay and other river systems including the Kennebec-Androscoggin that discharges just east of Casco Bay. The structure of the WMCC appears to be a sequence of freshened outflows that successively displace one another offshore as the current moves southwestward. The hydrographic structure of the WMCC has been characterized as plume-like, and the details of the physical oceanographic conditions in that region are presented in Geyer et al. (2004), Churchill et al. (2005) and Janzen et al. (2005).

The offshore veering of the EMCC and the degree of leakage into the WMCC appear to be a seasonal phenomena. Three years of moored current meter data from either side of the transition region around Penobscot Bay indicate that the alongshore convergence associated with the offshore veering of the surface and pycnocline waters of the EMCC commences in the spring or summer and diminishes in the fall.

There is intriguing preliminary evidence of a strong deep offshore veering of the EMCC that is out of phase with the near-surface veering and occurs in winter. These seasonal variations appear to be related to seasonal variations in the alongshore pressure gradient forces. In the spring and summer the outflow from the Penobscot River produces a low-density bulge of warm freshened water near the mouth of the Bay. In addition, the area of the Wilkinson basin has low-density surface and deep waters relative to the Jordan Basin to the east. These factors combine to produce an alongshore or along-gulf pressure gradient force directed upcoast that is maximum in the vicinity of Penobscot Bay. This western bulge in effect deflects the southwestward flowing water through a geostrophic adjustment process that produces an offshore flow. During the fall and winter the bulge and the alongshore surface density differences disappear, allowing the surface waters to flow uninterrupted toward the southwest. However, the deep waters in the EMCC are less dense than the deep waters of the WMCC due to tidal mixing, and this density gradient produces a baroclinic alongshore pressure gradient in the deep waters that is directed upcoast in the vicinity of Penobscot Bay and is associated with offshore deflection of the EMCC flow.

## Acknowledgements

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