# Section 4: Oceanographic Setting

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The ocean currents in Massachusetts Bay mix and transport water and material in the bay, and exchange water with the adjacent Gulf of Maine. The currents can conceptually be separated into tidal currents (which fluctuate 1–2 times each day), low-frequency currents caused by winds and river runoff (which typically fluctuate with a period of a few days), and a residual current (steady over a few weeks). Field observations (Butman, 1976; Geyer and others, 1992; Butman and others, 2004a; Butman and others, 2006) and simulations of the currents by numerical hydrodynamic models (for example Signell and others, 1996; Signell and others, 2000) provide descriptions of the flow pattern, strength, and variability of the currents. Field observations provide measurements of the currents at selected locations during specific periods of time, whereas model simulations provide a high-resolution view of the often complex spatial pattern of the flow. Direct observations and numerical simulations provide complementary descriptions of coastal currents that vary in space and time because of the complex bathymetry and coastal geometry, and because of the multiple processes (for example wind, river runoff, and currents in the Gulf of Maine) that drive the flow and change seasonally.

The oceanography of Massachusetts Bay may be conceptually separated into four seasonal intervals (following Geyer and others, 1992) based on the wind and surface waves (fig. 4.1); the temperature and thermal stratification of the water column (fig. 4.2); the salinity, salinity stratification, and horizontal salinity gradients caused by river discharge (fig. 4.3); and the density stratification, which results from the temperature and salinity distribution (fig. 4.4). From November through March (winter), the water column is vertically well-mixed, and the wind and surface waves are the largest of the year. In April and May (spring), the freshwater runoff from rivers is largest, and the water column is vertically salt-stratified. In spring, there may also be horizontal salinity gradients in the surface layers caused by the

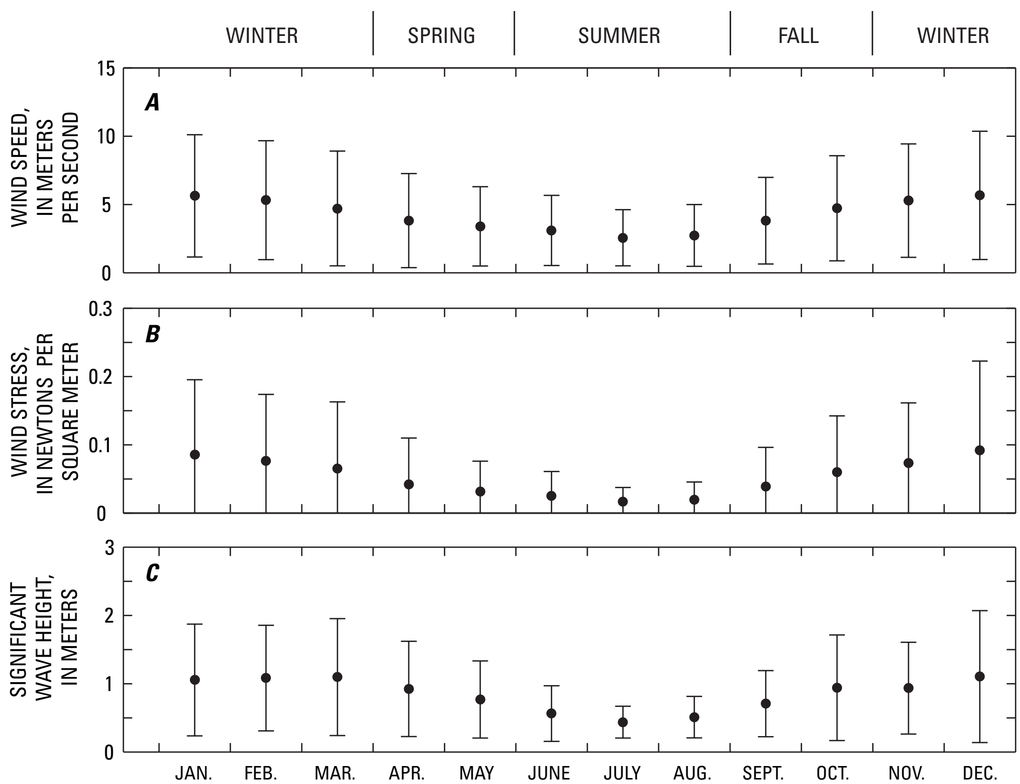


**Figure 4.1.** Monthly averaged *(A)* wind speed, *(B)* wind stress, and *(C)* significant wave height at NOAA Buoy 44013 (see fig. 3.1 for location). Vertical bars show one standard deviation (computed using hourly data) on each side of the mean value (dot). Data from the period November 1989 through December 2002 (Butman and others, 2004a).

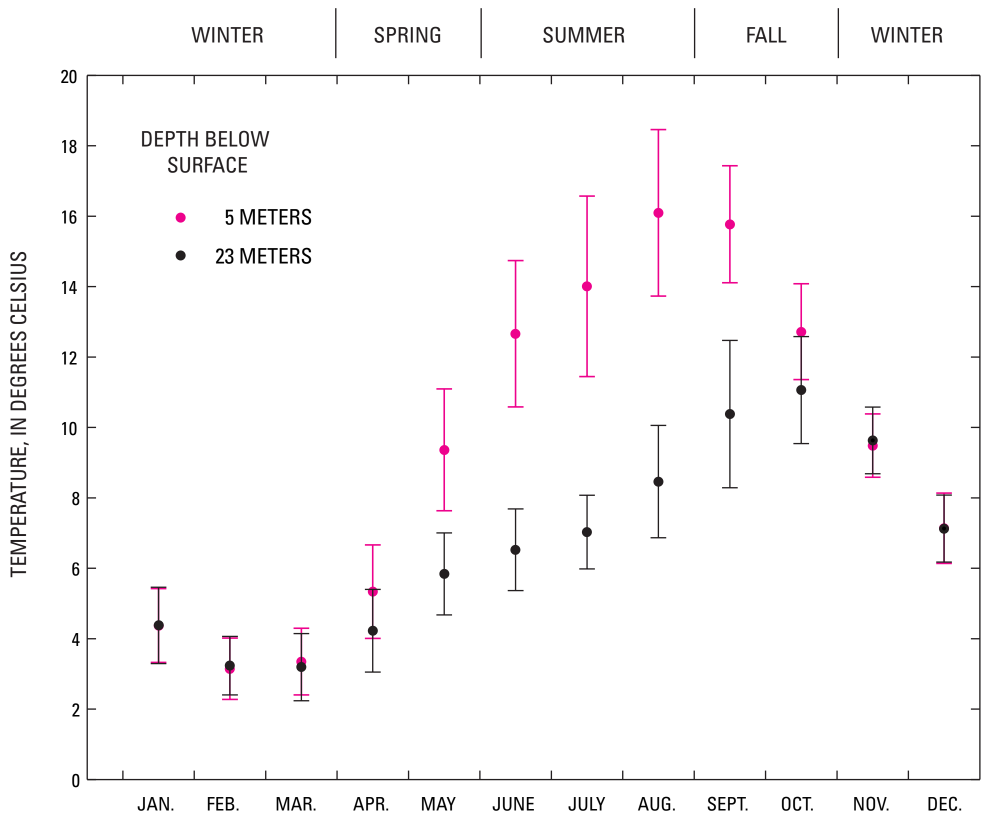


**Figure 4.2.** Monthly averaged water temperature at 5 and 23 m below the surface at the long-term monitoring site LT-A in western Massachusetts Bay (see fig. 3.1 for location). Vertical bars show one standard deviation (computed using hourly data) on each side of the mean value (dot). Data from the period November 1989 through December 2002 (Butman and others, 2004a).

rivers that discharge freshwater along the coast. From June through August (summer), the seasonal thermocline develops, the vertical density stratification reaches a maximum, and the winds and surface waves are the weakest of the year. From September through October (fall), the water cools, and the vertical stratification of the water column decreases from the strong summer stratification to well-mixed winter conditions.

Tidal current and elevation in Massachusetts Bay are dominated by semi-diurnal tides. The typical tidal range is about 2.6 m and varies from about 1.1 m to 4.1 m. At LT-A (fig. 3.1), the amplitudes of the semi-diurnal tides $M_2$ (period 12.42 hours), $N_2$ (period 12.66 hours) and $S_2$ (period 12.00 hours) are 1.29 m, 0.29 m, and 0.20 m, respectively, and the amplitudes of the diurnal tides $K_1$ (period 23.92 hours) and $O_1$ (period 25.82 hours) are 0.11 m and 0.14 m, respectively. The amplitude and phase of the tidal elevation is nearly uniform throughout the bay (fig. 4.5A). Tidal currents are largely bi-directional and flow into and out of the bay (fig. 4.5B). The strength of $M_2$ tidal current is less than 0.20 meters per second (m/s) except in the Race Point Channel, across the southern portion of Stellwagen Bank, and in the entrance to Boston Harbor where it exceeds 0.5 m/s (fig. 4.5B).

The low-frequency fluctuations in current are driven primarily by the wind and by horizontal density gradients. In Massachusetts Bay, these fluctuations are typically 0.1 m/s (figs. 4.6A, 4.6B), generally larger than the 0.01–0.05 m/s residual flow. Although the winds are strongest in winter, the low-frequency current fluctuations are largest in spring and summer (fig. 4.7). The strong currents in spring are driven by density gradients associated with lenses of freshwater from river runoff through Boston Harbor and from rivers that discharge into the Gulf of Maine to the north of Massachusetts

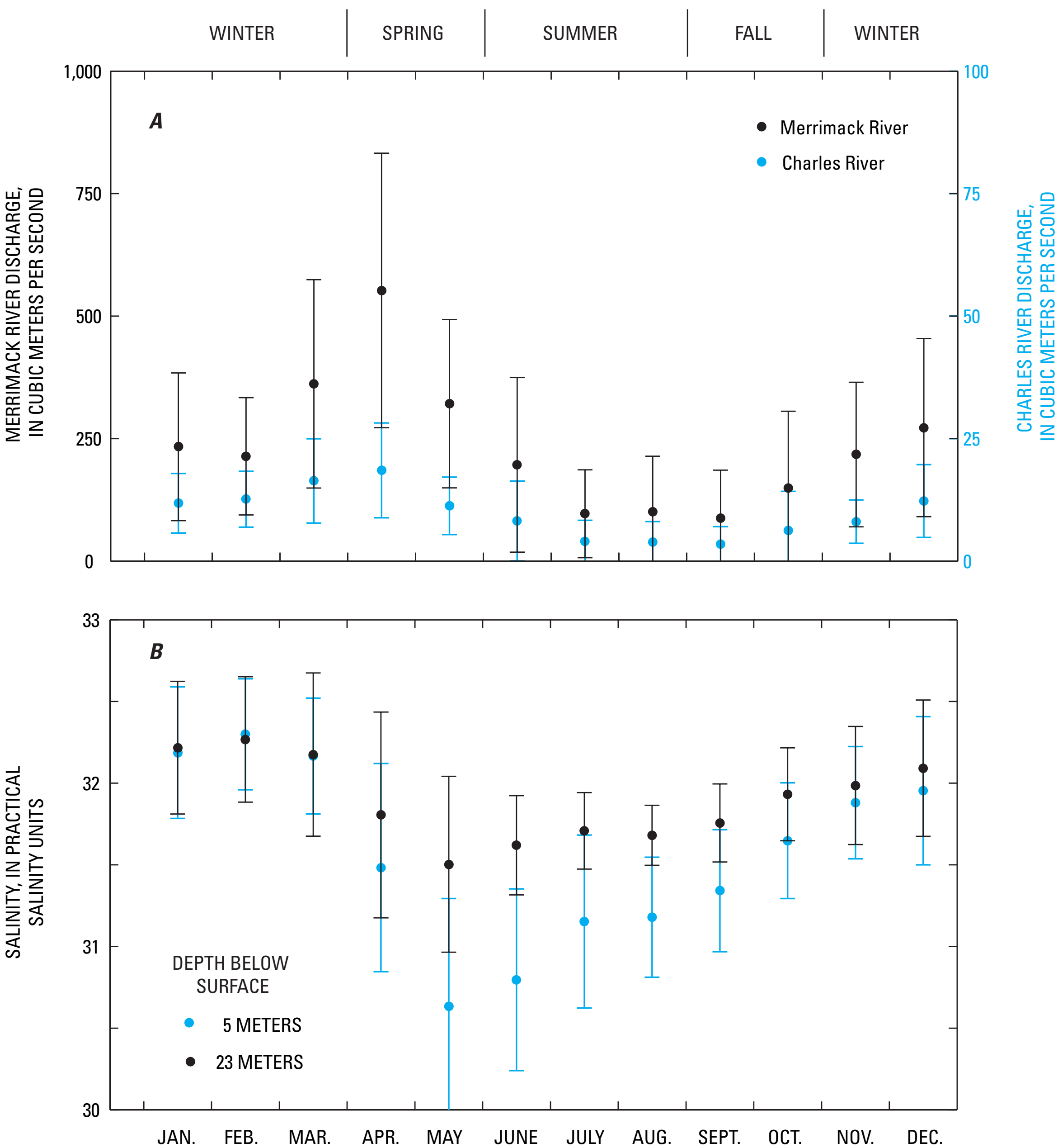


**Figure 4.3.** *(A)* Monthly averaged discharge for the Merrimack and Charles Rivers, and *(B)* salinity at 5 m and 23 m below the surface (10 m above the bottom) at the long-term monitoring site LT-A in western Massachusetts Bay (see fig. 3.1 for location). Vertical bars show one standard deviation (computed from daily observations of river flow and hourly data for salinity) on each side of the mean value (dot). Data from the period December 1989 through December 2002 (Butman and others, 2004a).

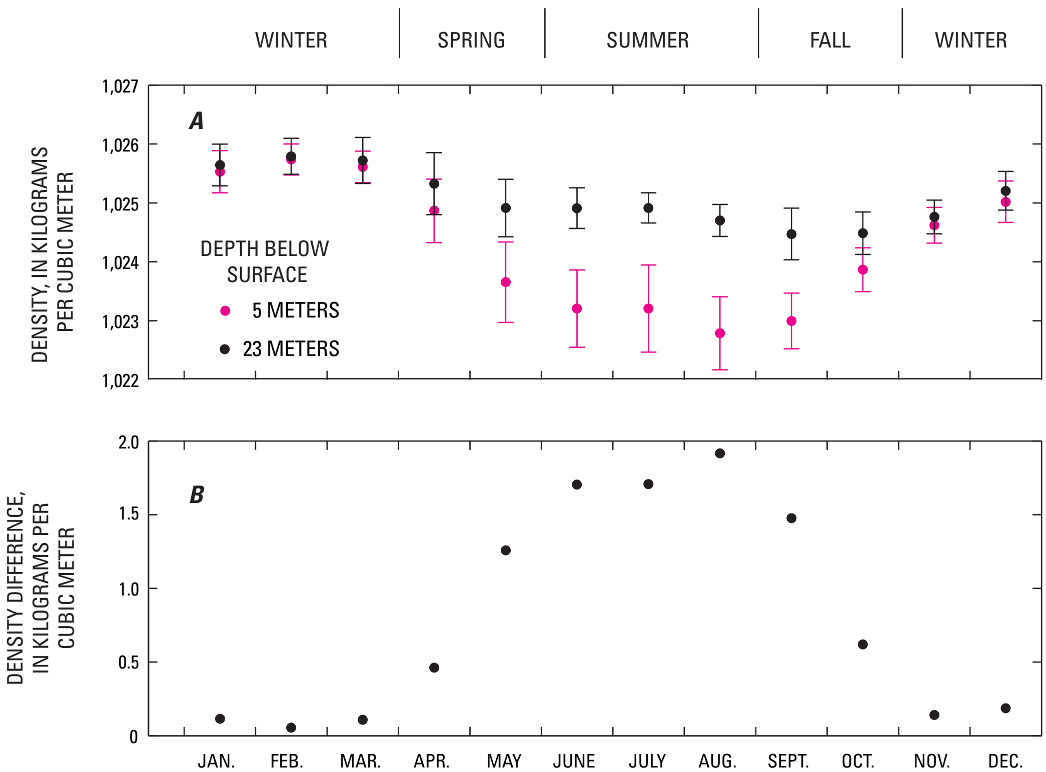


**Figure 4.4.** Monthly averaged water density at 5 and 23 m below the surface *(A)*, and the density difference between densities at 23 m and 5 m *(B)* at long-term monitoring site LT-A in western Massachusetts Bay (see fig. 3.1 for location). Vertical bars show one standard deviation (computed using hourly data) on each side of the mean value (dot). Data from the period December 1989 through November 2002 (Butman and others, 2004a).

Bay (Butman, 1976; Geyer and others, 1992). Along the western shore of Massachusetts Bay and in the Gulf of Maine Coastal Current, the low-frequency currents are strongest in the along-coast direction, but in the northwestern corner of Massachusetts Bay, over Stellwagen Bank, and in the center of Cape Cod Bay, the low-frequency currents do not have a strong preferred orientation (the ellipses in figs. 4.6A, 4.6B are more circular).

Information on the residual flow pattern in Massachusetts Bay comes from field observations (figs. 4.6A, 4.6B) and from model simulations. Simulations of the currents in Massachusetts Bay with a three-dimensional hydrodynamic model (Signell and others, 1996) for winter (defined as November through February) (fig. 4.8) and summer (defined as June through August) (figs. 4.9A, 4.9B) and averaged for the years 1990–1992, provide a picture of the flow pattern in Massachusetts Bay that is quite consistent with the limited field observations (figs. 4.6A, 4.6B). In both seasons, the Gulf of Maine Coastal Current flows to the southeast at 0.05–0.1 m/s to the east of Stellwagen Bank. In winter, some of the Maine Coastal Current enters Massachusetts Bay south of Cape Ann, initially flowing to the south at a few centimeters per second (fig. 4.8). Some of the inflow turns eastward and exits Massachusetts Bay across Stellwagen Bank, some continues southward across Massachusetts Bay into Cape Cod Bay, and some flows southwestward toward Boston, then turns southeastward toward Cape Cod Bay. The residual flow is strongest, about 0.05 m/s, in the current along the western shore of Massachusetts Bay; a water particle takes about 15 days to reach the southern part of Cape Cod Bay from the area of the Massachusetts Bay outfall offshore of Boston (fig. 1.5). The flow in central Massachusetts Bay is very weak (less than a few centimeters per second); a particle takes more than 100 days to travel from Cape Ann to Cape Cod Bay.

In summer, at a depth of 5 m, which is above the seasonal thermocline, there is a southerly flow into Massachusetts Bay south of Cape Ann (fig. 4.9A). In contrast to the winter pattern however, all this flow occurs in the center of Massachusetts Bay, is joined by upwelled water from the northwest corner of Massachusetts Bay, and exits to the east across Stellwagen Bank; no surface flow enters Cape Cod Bay. Along the western shore, there is a weak flow to the northwest. The flow pattern in Cape Cod Bay includes a clockwise circulation centered southeast of Plymouth Harbor and a smaller counterclockwise circulation south of Provincetown. At 25-m depth, which is below the seasonal thermocline, the principal features of the residual flow are the southeastward Maine Coastal Current, and a southerly flow along the western side of Massachusetts Bay at about the 40-m isobath (fig. 4.9B). In contrast to the near-surface flow, this southerly flow feeds a counterclockwise flow in Cape Cod Bay that exits north of Race Point. In winter and summer, with the exception of the Gulf of Maine Coastal Current, the residual flows are less than 0.05 m/s and particle trajectories are most influenced by the tidal currents and the low-frequency flow.

A

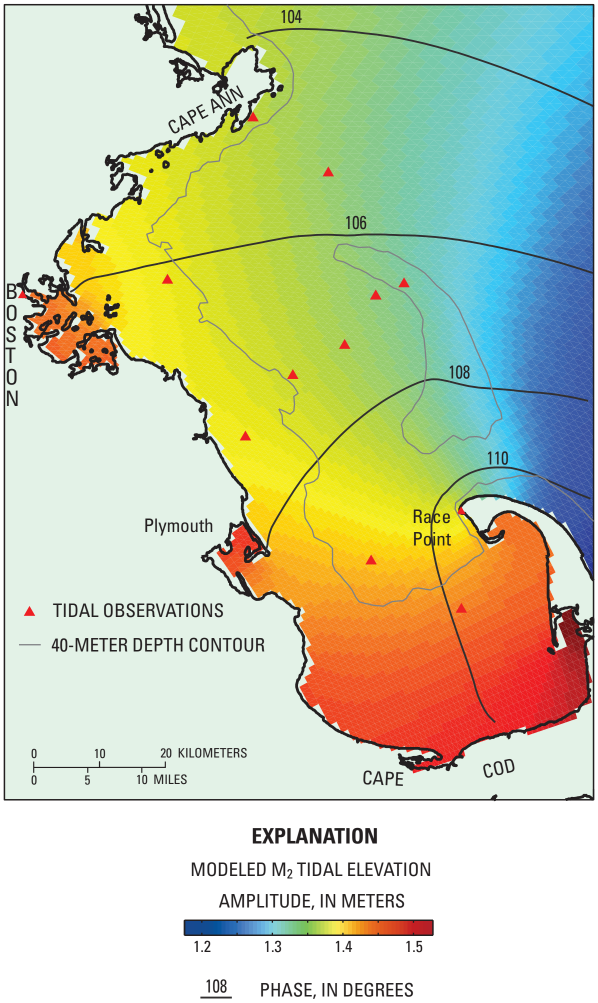


**Figure 4.5 *(A).*** $M_2$ tidal elevation in Massachusetts Bay, calculated with the Regional Ocean Modeling System (ROMS). The background color is the amplitude of the $M_2$ tide. The phase of the $M_2$ tide is shown as contours and varies by about 4° (8 minutes) across Massachusetts Bay. Observations, obtained at locations marked by red triangles, compare well to the predicted amplitude and phase.

B

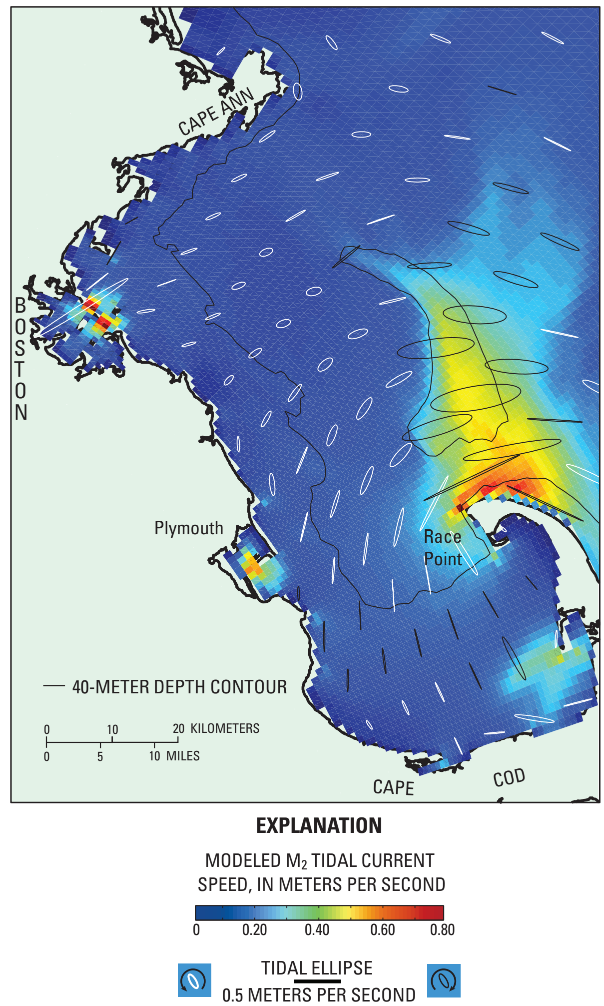


**Figure 4.5 *(B).*** Surface $M_2$ tidal current ellipses, calculated with the Regional Ocean Modeling System (ROMS). The background color is the magnitude of the major axis of the tidal ellipse. The tidal current vector originates at the center of the ellipse and sweeps out the ellipse every tidal cycle. Currents in the ellipses shown in white rotate counterclockwise; currents in the ellipses shown in black rotate clockwise. The size of the ellipse shows the excursion of a water particle at map scale. The tide flows into and out of Massachusetts Bay, essentially in phase throughout the bay. The strongest tidal currents are in Race Point Channel, over southern Stellwagen Bank, and in the entrances to Boston and Plymouth Harbors.

A

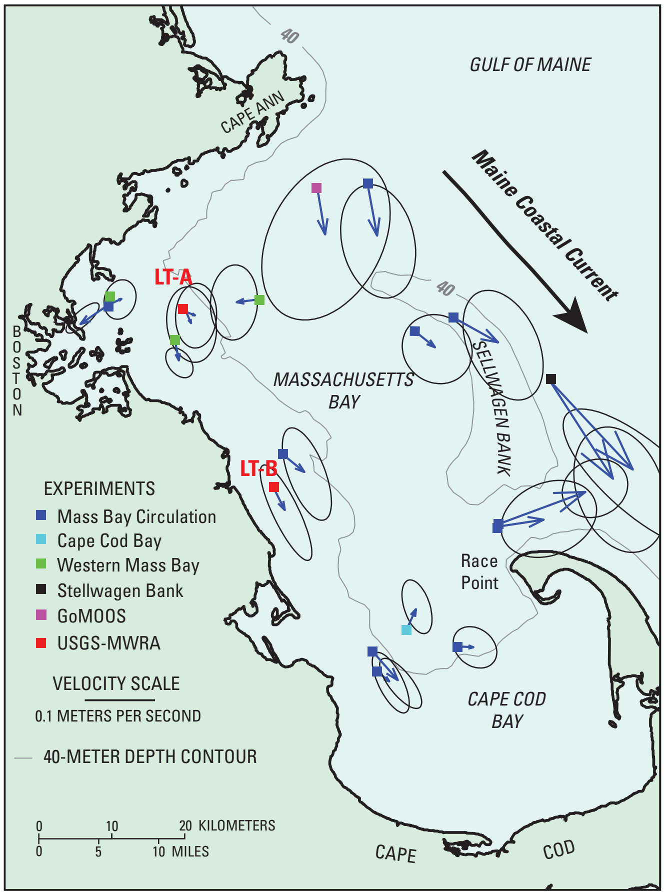


**Figure 4.6 *(A).*** Winter (November through February) near-surface mean flow and low-frequency current ellipses observed in Massachusetts Bay during experiments conducted between 1986 and 2005. The observed winter mean flow (blue arrows) and the variability (shown as an ellipse centered around the tip of the mean-flow arrow) are shown for near-surface currents (measured 2–8 m below sea surface). Typically, the daily averaged current originates at the station symbol (colored squares) and flows toward any location within the ellipse. In general, the low-frequency fluctuations are larger than the mean. These data were obtained from the Massachusetts Bay Circulation Experiment (winter 1990–1991; Geyer and others, 1992), U.S. Geological Survey-Massachusetts Water Resources Authority (USGS-MWRA) long-term observations (winter 1990–2002 at LT-A and winter 1997–2002 at LT-B; Butman and others, 2004a), Gulf of Maine Ocean Observing System (GoMOOS; winter 2001–2005), Stellwagen Bank (winter 1994; USGS data archives), western Massachusetts Bay (winter 1987; USGS data archives), and Cape Cod Bay (winter 1986; USGS data archives).

B

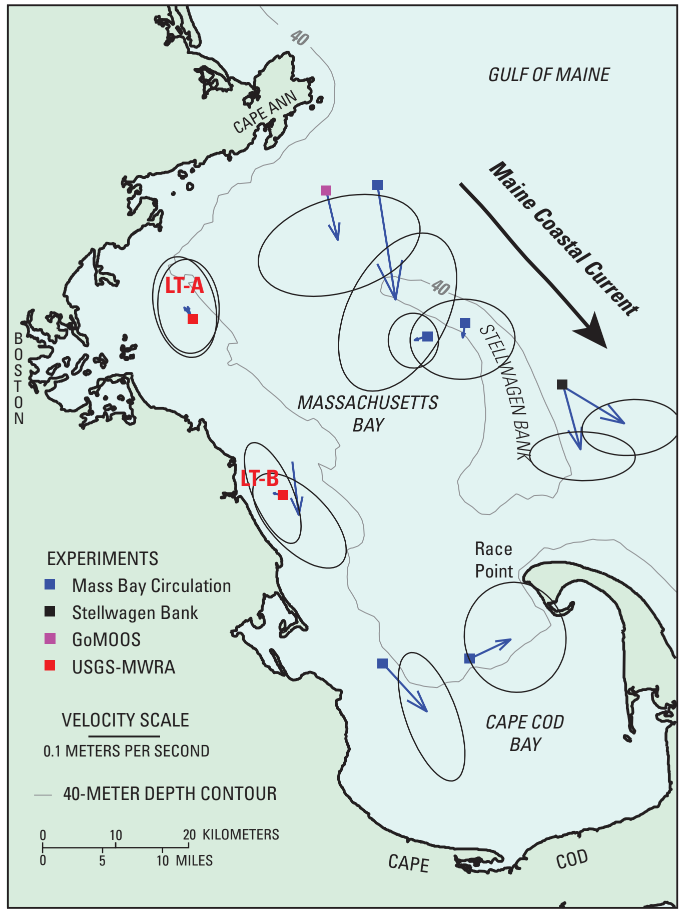


**Figure 4.6 *(B).*** Summer (June through August) near-surface mean flow and low-frequency current ellipses observed in Massachusetts Bay during experiments conducted between 1988 and 2004. The observed summer mean flow (blue arrows) and the variability (shown as an ellipse centered around the tip of the mean-flow arrow) are shown for near-surface currents (measured 2–8 m below sea surface). Typically, the daily averaged current originates at the station symbol (colored squares) and flows toward any location within the ellipse. In general, the daily fluctuations are larger than the mean. These data were obtained from the Massachusetts Bay Circulation Experiment (summer 1990; Geyer and others, 1992), U.S. Geological Survey-Massachusetts Water Resources Authority (USGS-MWRA) long-term observations (summer 1990–2002 at LT-A and summer 1998–2002 at LT-B; Butman and others, 2004a), Gulf of Maine Ocean Observing System (GoMOOS; summer 2001–2004), and Stellwagen Bank (summer 1994, USGS data archives).


**Figure 4.7.** Monthly-averaged low-frequency current speed (computed from low-pass filtered east and north current components) at 5 and 23 m (10 m above the bottom) at long-term monitoring site LT-A in western Massachusetts Bay (fig. 3.1). The low-frequency current speed is a measure of the typical strength of the low-frequency current. Vertical bars show one standard deviation (computed using 6-hour data) on each side of the mean value (dot).

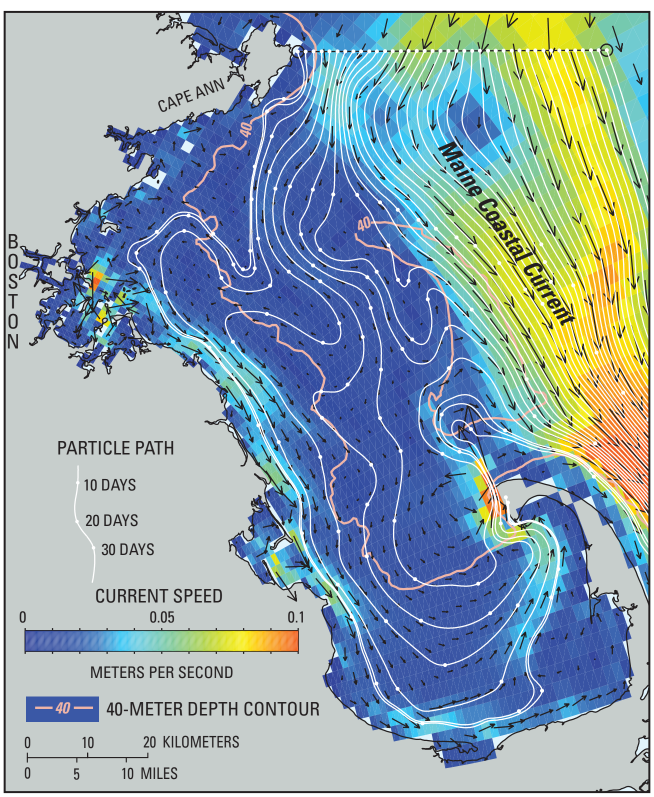


**Figure 4.8.** Depth-averaged mean flow in Massachusetts Bay in winter calculated from numerical simulations for the months November–February 1990–1992, when the water column is vertically well-mixed. The flow pattern is visualized by tracks of particles (white lines) introduced along the dashed line to the east of Cape Ann. The white dots along the tracks indicate positions of the particles every 10 days. The black arrows show the vector current at every second grid cell; the background color is the scalar current speed. The simulations show a flow to the southeast of 0.05–0.1 m/s in the Gulf of Maine to the east of Massachusetts Bay (the Maine Coastal Current), some of which enters the bay south of Cape Ann. Within Massachusetts Bay, the depth-averaged residual flow is strongest (about 0.05 m/s) along the western shore.

*A*

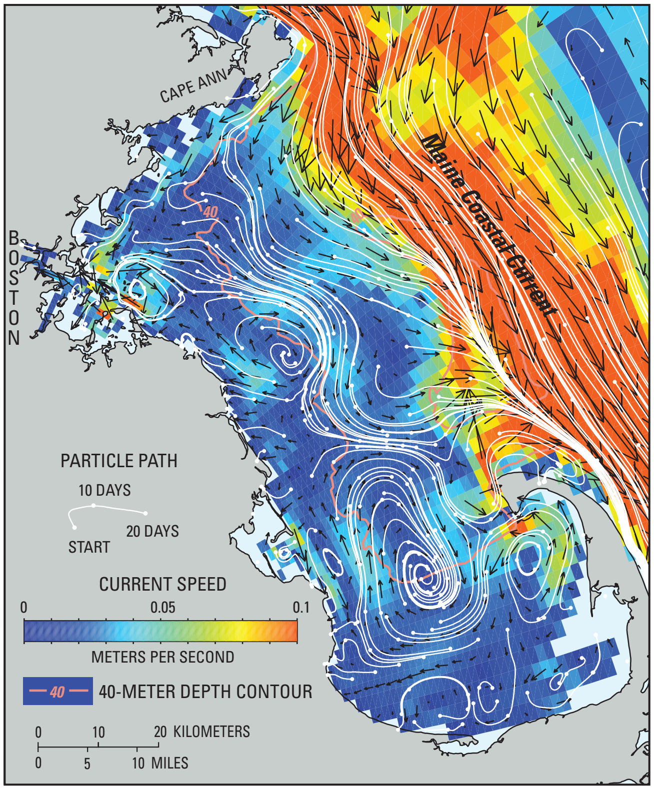


**Figure 4.9** ***(A).*** Mean flow in Massachusetts Bay in summer at 5-m water depth calculated from numerical simulations for the summer months June–August 1990–1992, when the water column is stratified. The flow pattern is visualized by tracks of particles (shown as white lines) introduced at every fourth model-grid cell. Each particle track is 20 days long; white dots indicate the beginning of the track and the particles' positions at 10 and 20 days (end). The black arrows show the vector current at every second grid cell; the background color is the scalar current speed.

*B*

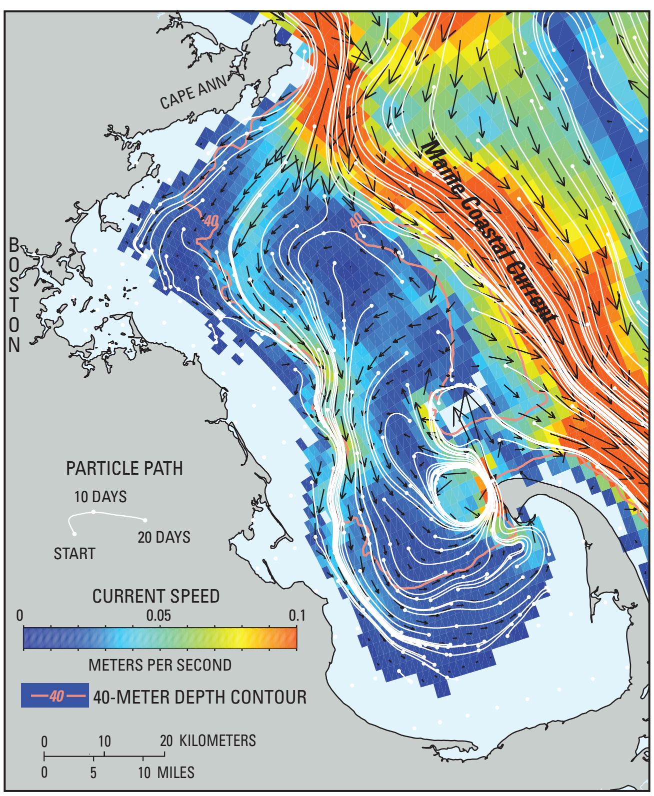


**Figure 4.9** ***(B).*** Mean flow in Massachusetts Bay in summer at 25-m water depth calculated from numerical simulations for the summer months June–August 1990–1992, when the water column is stratified. The flow pattern is visualized by tracks of particles (white lines) introduced at every fourth model-grid cell. Each particle track is 20 days long; white dots indicate the beginning of the track and the particles' positions at 10 and 20 days (end). The black arrows show the vector current at every second grid cell; the background color is the scalar current speed.