Section 6: Predicting the Transport and Fate of Sediments Caused by Northeast Storms

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An overall goal of USGS research in Massachusetts Bay (fig. 1.5) is to develop a regional understanding of the transport and long-term fate of sediment particles and associated contaminants. This sediment-transport research program has three components: (1) mapping the sea floor to determine the distribution of sediments and contaminants (Section 2), (2) collecting long-term oceanographic observations of currents and sediment movement to identify key processes causing sediment transport and to provide data for testing numerical models (Sections 3 and 4), and (3) developing a coupled hydrodynamic sediment-transport model to explore the transport and fate of particles on a regional basis. The semi-enclosed geometry of Massachusetts Bay, the water depth that ranges from 30 to 90 m between the banks and basins, and the varied sediment texture provide a natural laboratory for the development and testing of models for the transport and long-term fate of sediments.

Over the last 25 years, observational and modeling studies have identified sediment transport by combined waves and currents as one of the most important processes of sediment transport on continental shelves. The bottom stress caused by the oscillatory currents associated with surface waves (Grant and Madsen, 1979) resuspend sediments; wind-driven, density-driven, and/or tidal currents can carry these sediments over long distances. The long-term observations at LT-A (fig. 3.1) show that storms with large surface waves are a key process that causes bottom sediment resuspension in Massachusetts Bay (fig. 6.1); tidal currents, wind-driven currents, or currents associated with spring runoff alone are typically not strong enough to resuspend sediments.

In Massachusetts Bay, a threshold bottom stress of about 0.12 Newtons per square meter (N/m^2)(equivalent to a steady current of about 0.2 m/s 1 meter above bottom, or a wave orbital current of about 0.14 m/s with a period of 12 seconds 1 meter above bottom) has been observed to be sufficient to resuspend fine-grained (silt and clay) bottom sediments in Stellwagen Basin (Butman and others, 2006). Note that this threshold for sediment resuspension is a factor of two larger than the estimate presented in Butman and others (2006) because of an erroneous factor of 0.5 in the drag formula they used to estimate bottom stress from near-bottom current. The percentage of time this threshold is exceeded by surface waves decreases exponentially with water depth and is less than about 4 percent of the time in winter in water deeper than 50 m (fig. 6.2); at any given depth, resuspension is more frequent in winter than in summer. Coarser sediments that require a larger resuspension stress will be resuspended less frequently.

The largest waves in Massachusetts Bay are associated with winds from the northeast (fig. 6.3) because of the unobstructed fetch from the Gulf of Maine. The 12 strongest storms between 1990 and 2005, based on the strength and duration of the bottom wave stress above the resuspension threshold, all had winds from the north or northeast quadrant (winds from a direction of 357º to 66º, measured clockwise from north) (table 6.1). The two strongest storms were the northeaster “Blizzard of 92” in December 1992 and the “Halloween” or “Perfect Storm” in October 1991, both with winds from the northeast quadrant (table 6.1). The long-term fate of particles in Massachusetts Bay is the cumulative result of their resuspension and transport by a variety of processes, but especially by storms with winds from the northeast (northeast storms) because of the large waves driven by winds from this direction.

Model simulations using a coupled surface-wave, hydrodynamic, and sediment-transport model have been carried out to improve understanding of sediment transport and fate in Massachusetts Bay under simplified northeast storm conditions. (Warner and others, in press). These simulations were driven by tides and by winds from the northeast. Winds characteristic of northeast storms in March 1997 and December 1992 (table 6.1) were used in these simulations to drive the surface-wave and circulation models. Wind direction used in the simulations for the March 1997 storm was constant from 12º (measured clockwise from north) and wind direction used for the December 1992 storm was constant from 50º; both directions are close to the average wind direction during these storms. When winds blow over Massachusetts Bay, the semi-enclosed geometry causes an elevation setup against the coast in the down-wind direction. This setup and the surface wind stress causes a flow pattern with a component of surface flow in the direction of the wind in the shallow water along the coast in Massachusetts Bay and along the outer Cape, and flow opposite to the direction of the wind in deeper parts of Massachusetts or Cape Cod Bay (fig. 6.4). The combined tidal and wind-driven currents, that vary in space and time, transport sediments that are resuspended during storms. Sediments are deposited on the sea floor at locations where and when the bottom stress falls below the resuspension threshold.

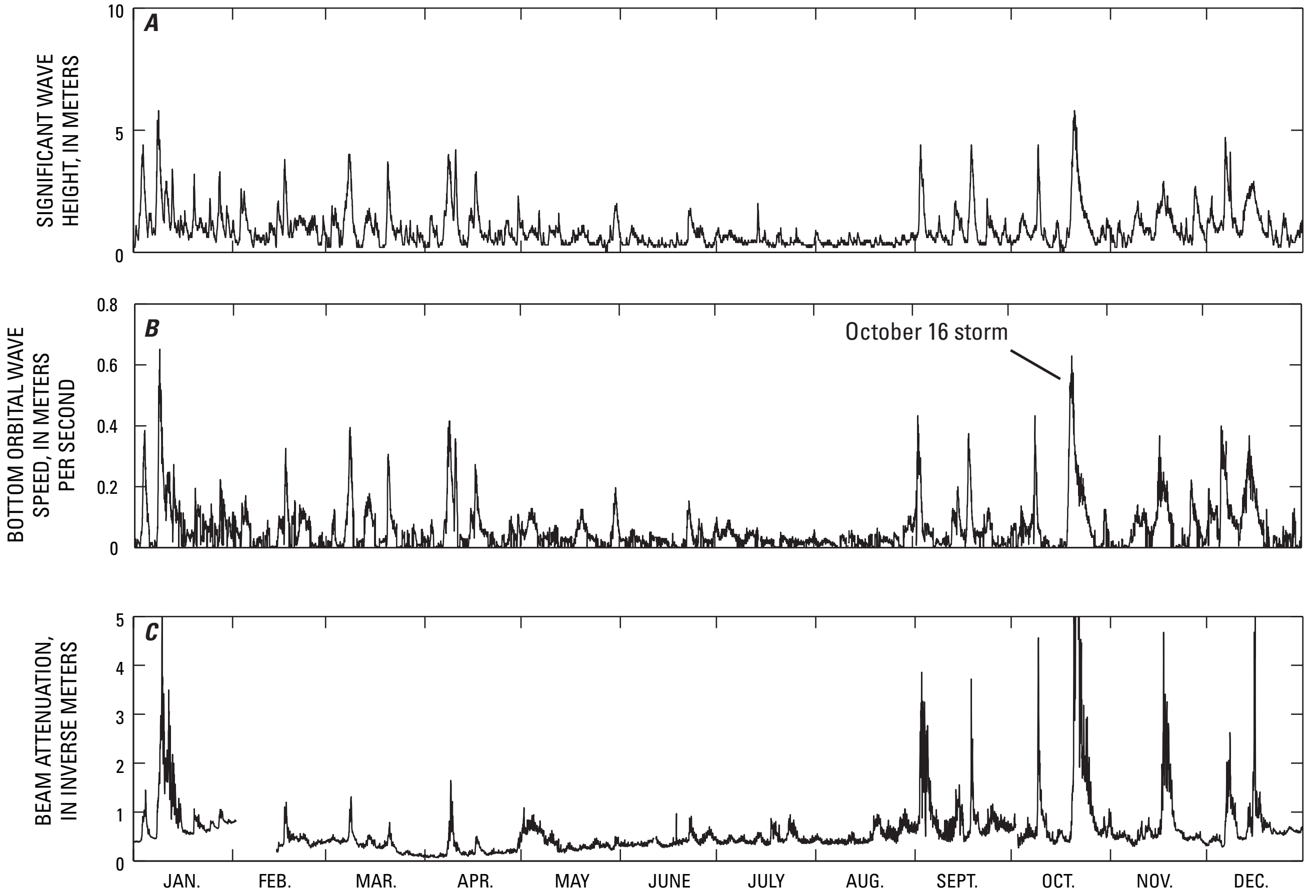

Figure 6.1. *(A)* Time series of significant wave height (measured at NOAA Buoy 44013; fig. 3.1), *(B)* bottom orbital wave speed at 30-m water depth (calculated from surface wave observations), and *(C)* beam attenuation (a measure of suspended sediment concentration), measured 2 m above the bottom at LT-A (fig. 3.1) in western Massachusetts Bay for 1996. Sediment concentrations are higher in the near-bottom water whenever wave-induced currents are large. Based on the duration and strength of near-bottom wave stress, the October 16, 1996 storm was the 11th largest storm from 1990 to 2005 (table 6.1). Near-bottom wave velocities and stress shown in figures 6.1, 6.2, and 6.3 and in table 6.1 were calculated using the methods outlined in Wiberg and Sherwood (in press).

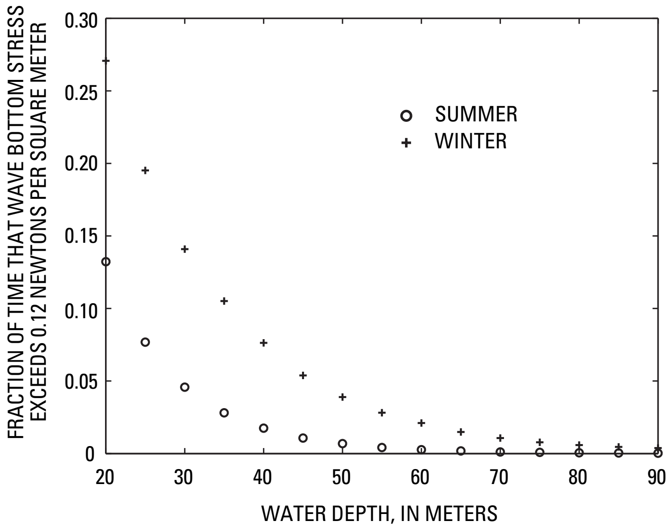

Figure 6.2. Percentage of time that bottom stress caused by surface waves exceed threshold of 0.12 N/m^2 as a function of water depth and season. The bottom stress was calculated for winter (October through March) and summer (April through September) from wave observations at NOAA Buoy 44013 (fig. 3.1) for the period 1990 through 2005. At 50-m water depth, bottom-wave stress exceeded 0.12 N/m^2 about 4 percent of the time in winter and about 1 percent of the time in summer.

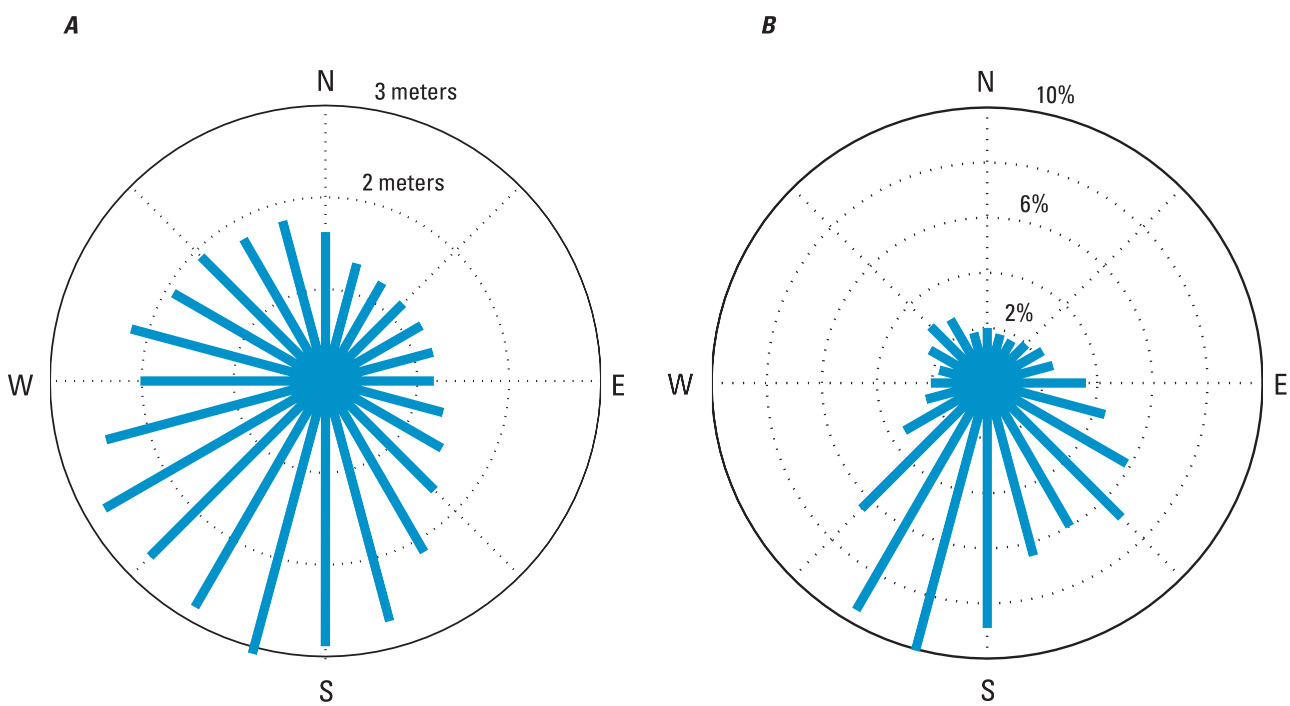

Figure 6.3. *(A)* Average significant wave height in meters as a function of wind direction for winds greater than 10 m/s, and *(B)* percentage of bottom wave stress greater than 0.12 N/m^2 at 30-m water depth as a function of wind direction. The wind blows toward the direction indicated. Wave data were obtained at NOAA Buoy 44013 in Massachusetts Bay (fig. 3.1), and wave stress was calculated from surface wave observations. The largest occurrence of near-bottom wave stress greater than threshold is associated with winds from the north and northeast (blowing toward the south and southwest). The wave bottom stress associated with winds from the northwest most likely reflects waves generated by storms that have northeast winds (on the northwestern side of the storm system) over the Gulf of Maine that reach Massachusetts Bay when winds are from the northwest over Massachusetts Bay following the storm system.

Table 6.1. Twelve strongest storms from 1990 through 2005, based on the sum of the wave bottom stress above sediment-resuspension threshold (0.12 N/m^2) during storms at a water depth of 30 m. A storm was defined as a period of time when wave bottom stress exceeded the resuspension threshold for at least 6 hours; wave stress had to fall below the threshold for at least 12 hours to initiate a new storm. Wave bottom stress was calculated from wave observations at NOAA Buoy 44013. The two largest storms were the December 11, 1992 "Blizzard of '92'" and the "Halloween Storm" or "Perfect Storm" of October 28, 1991.

[Wind speed (in meters per second) and wind direction from which the wind blows (direction in degrees measured clockwise from north) are the components of vector-averaged wind for the period of the storm when the wind stress was greater than 0.2 Newtons per square meter (wind speed of 11.5 meters per second); SWH is significant wave height (in meters); dominant wave period (in seconds) is period of surface waves; average u_b (in meters per second) is the bottom wave current at 30-m water depth calculated from the surface wave observations over the duration of the storm; the excess stress is the sum of the stress above the resuspension threshold at 30-m water depth over the duration of the storm. The excess stress is used to rank the storms. The long duration of the 28 January 1998 storm is a result of two storms that occurred one after the other; they are lumped together as one storm in this analysis. The long duration of some of the other storms reflect waves that continue to propagate into Massachusetts Bay after a storm has passed. —, no wind data are available for storm 4]

Storm rank	Start date	Storm duration (hours)	Wind speed (m/s)	Wind direction (degrees)	Average SWH (m)	Dominant wave period (s)	Average u_b (m/s)	Average bottom stress (N/m^2)	Excess stress (hr-N/m^2)
1	11-Dec-92	142	17.1	54	4.1	12.7	0.51	1.3	173
2	28-Oct-91	127	15.0	24	3.7	11.5	0.44	1.1	126
3	6-Dec-03	88	14.6	7	4.6	11.0	0.51	1.4	118
4	5-Mar-01	116	—	—	4.0	11.8	0.44	1.1	117
5	28-Jan-98	254	14.7	15	2.5	11.0	0.24	0.4	78
6	11-Dec-93	186	13.5	10	3.0	10.6	0.27	0.5	70
7	23-Jan-05	52	14.8	357	4.7	11.3	0.51	1.4	66
8	31-Mar-97	76	14.8	8	3.8	10.1	0.39	0.9	59
9	20-Oct-04	226	12.0	25	2.5	10.5	0.23	0.4	57
10	4-Mar-93	80	14.4	45	3.7	11.9	0.40	0.9	57
11	19-Oct-96	138	15.7	66	2.9	10.9	0.29	0.5	56
12	23-Oct-05	98	11.6	7	3.4	10.5	0.32	0.7	56

Surficial Sediment Distribution

A simulation using the coupled hydrodynamic sediment-transport model was carried out to explore how a mixture of sediments (sand and silt-sized particles) placed on the sea floor throughout Massachusetts Bay would be winnowed and redistributed under a series of 10 northeast storms, each of them similar to the December 1992 storm. The simulations show the location of increased bottom stress, sediment resuspension, and bathymetric change (fig. 6.5). The combined wave and current stress at the peak of the storm is greatest in the shallow water along the coastline and on the crest of Stellwagen Bank because of increased bottom-wave orbital velocities in shallow water. The bottom stress is lower in Stellwagen Basin, where the near-bottom wave currents are attenuated in the deep water, and in Cape Cod Bay because the eastern arm of the Cape shelters the bay from waves from the northeast. Along the western shore of Massachusetts Bay, combined wave and current stress is high between Boston and Plymouth, and decreases between Plymouth and Barnstable (fig. 6.5A). At the end of the 10-storm simulation, net erosion of as much as 0.05 m has occurred along the crest of Stellwagen Bank, along the western shore of Massachusetts Bay north of Plymouth, in eastern Cape Cod Bay, and along the eastern edge of Cape Cod. Sediments were deposited south of Cape Ann, in Stellwagen Basin immediately west of Stellwagen Bank, and in Cape Cod Bay in a band extending from the Cape Cod Canal to Provincetown. Sediments were also deposited south of Plymouth; these sediments were eroded from the area north of Plymouth and transported southeastward along the coast (fig. 6.5B). This depositional site may disappear as the upstream source is removed.

The qualitative agreement between the present distribution of sediments and the distribution following the multiple-storm simulation is consistent with the hypothesis that sediment resuspension, transport and deposition associated with northeast storms play a key role in determining the sediment distribution in Massachusetts Bay. Mixtures of sediment introduced into the system

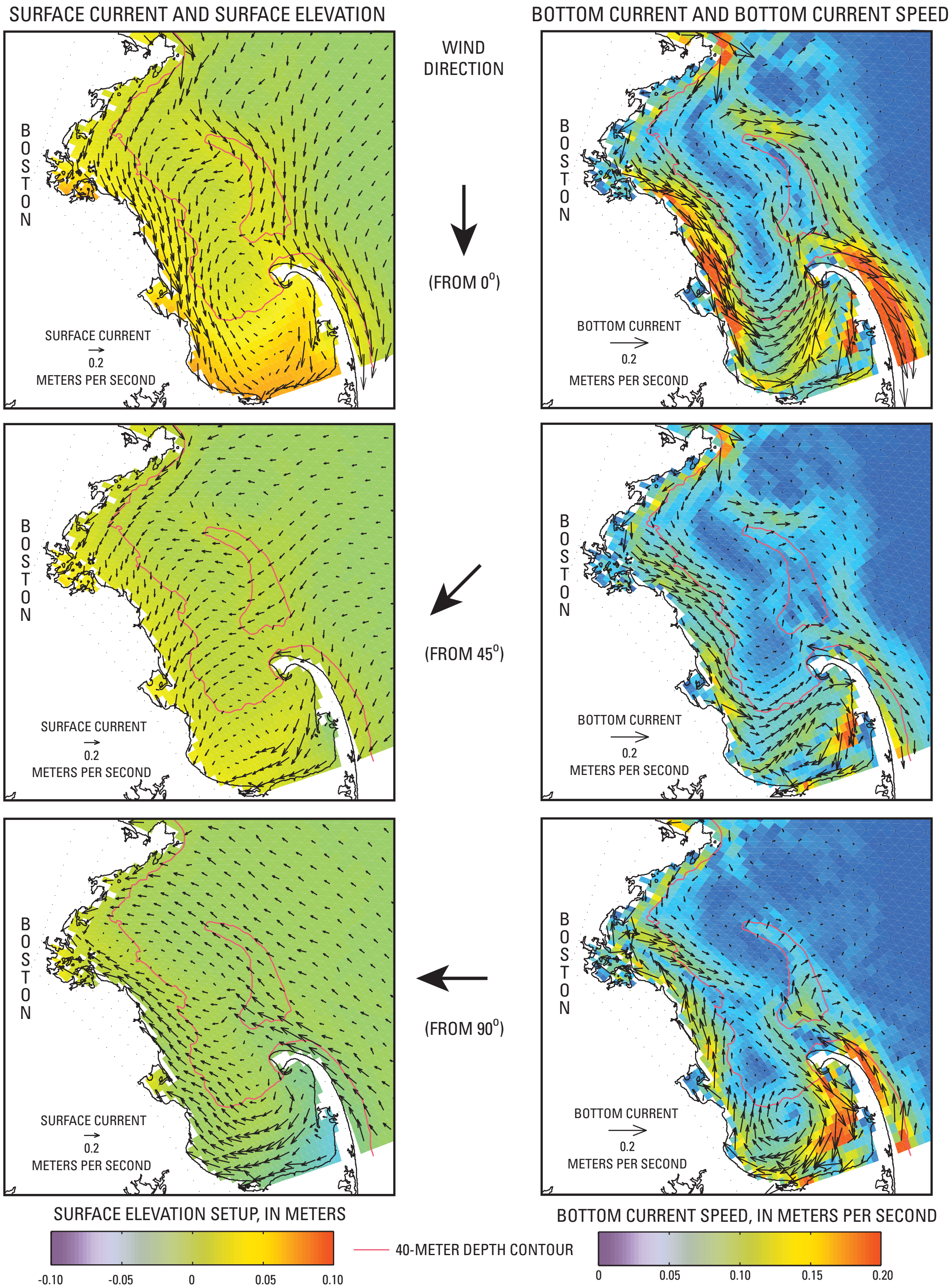

Figure 6.4. Steady-state response of surface (left) and near-bottom currents (right) driven by a surface wind of 10 m/s (20 knots, surface stress of 0.14 N/m^2) from a direction of 0°, 45°, and 90° measured clockwise from north (indicated by bold arrow). Arrows on the maps show current magnitudes and directions. On the surface current figures, color indicates the set-up or set-down of the water surface from mean sea level. On the bottom current figures, color indicates the current speed. When wind blows over Massachusetts Bay, the semi-enclosed geometry causes an elevation setup against the coast in the down-wind direction. This setup and surface wind stress cause a flow pattern with a component of surface flow in the direction of the wind in the shallow water along the coast in Massachusetts Bay and along the outer Cape, and flow opposite to the direction of the wind in deeper parts of Massachusetts Bay or Cape Cod Bay. The flow along the western shore of Massachusetts Bay switches from southeastward to northwestward at a wind direction of about 70°. Note that the bottom current map shows the flow pattern at the bottom, not at the same level.

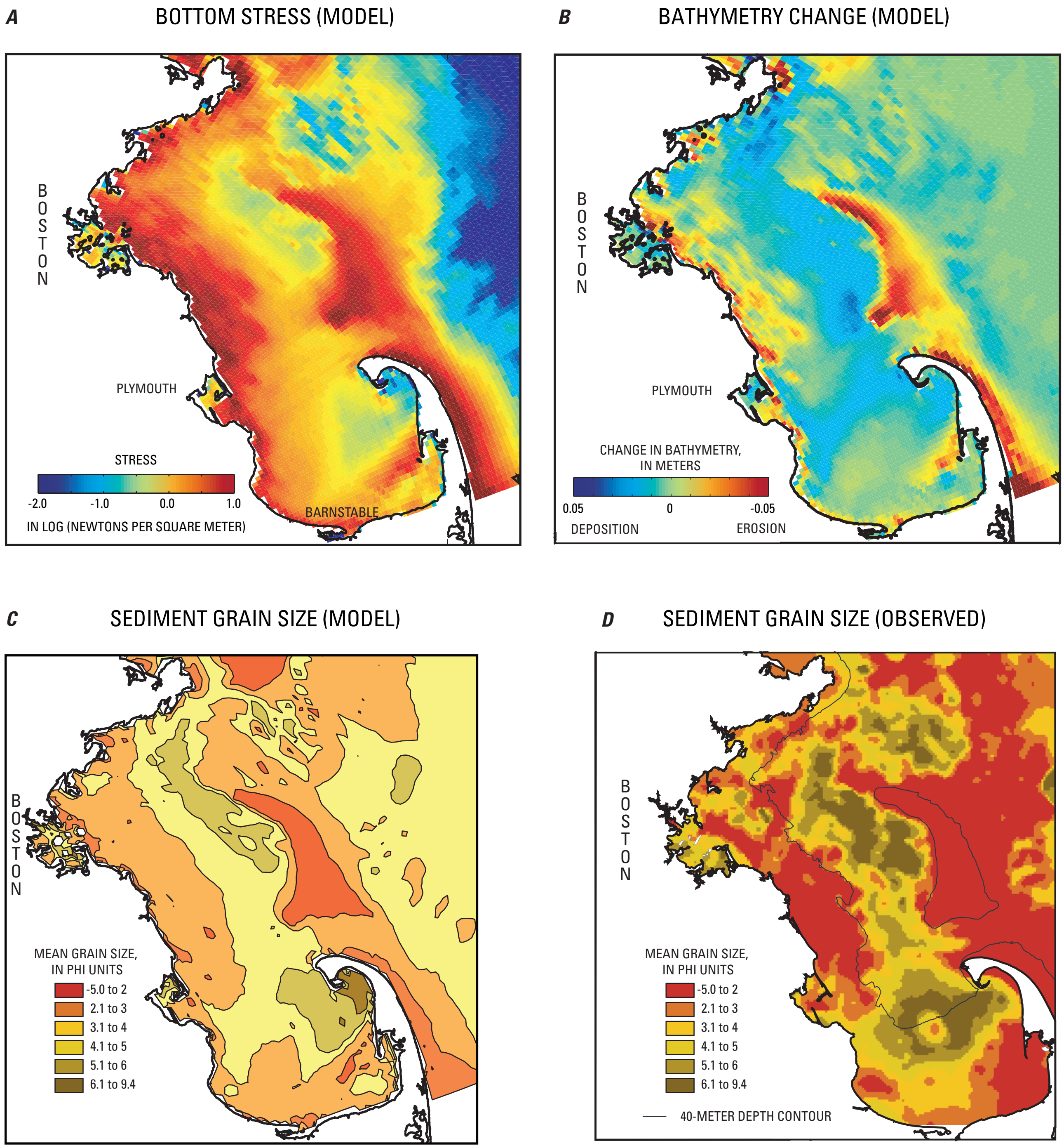

Figure 6.5. Results from a model simulation of the evolution of a sediment bed initially composed of a combination of grain sizes in response to a sequence of 10 idealized northeast storms, each of which was modeled after the December 1992 storm with winds from a direction of 50°: *(A)* The instantaneous combined wave-current bottom stress at the peak of the storm, *(B)* the change in bathymetry, and *(C)* the final mean surficial sediment grain size. The observed surficial sediment grain-size distribution *(D)* qualitatively matches the modeled surficial grain size after 10 storms *(C)*. The main areas of fine-grained sediment accumulation are Stellwagen Basin and Cape Cod Bay. Phi units are $-\log_2$ (sediment grain size in millimeters); larger numbers indicate finer sediments.

would be resuspended, sorted, and deposited in a similar pattern. However, the present sediment distribution also reflects the glacial history of the region. Glaciers transported and deposited gravel, cobbles, and boulders that could not be moved by even the strongest northeast storms. For example, the coarse sediments found to the east of Stellwagen Bank are not the result of transport by northeast storms, but are most likely the result of deposition during the last glaciation.

Pathways of Sediment Transport Caused by Northeast Storms

The MWRA was established in 1985 to clean up contamination of Boston Harbor resulting from the long-term discharge of sewage sludge and effluent. Elimination of sewage sludge discharge to the harbor, addition of secondary treatment, and moving the discharge of treated effluent to a new ocean outfall 15.2 km offshore in Massachusetts Bay (in deeper water and away from the coast; fig. 1.5) has resulted in improved water quality in Boston Harbor and no apparent change in Massachusetts Bay, as predicted (Signell and others, 2000; Section 5). Although the loading of solids and metals has been reduced by a factor of 4 and 6, respectively, since 1990 (Werme and Hunt, 2004; fig. 7.2), it was of interest to compare the long-term fate of particles introduced into Boston Harbor with particles introduced into western Massachusetts Bay at a site near the new outfall.

The metal silver, introduced to the sewage system in the past largely by the film-processing industry, can be used as a sewage particle tracer because these particles can acquire silver concentrations 1,000 times higher than those found in uncontaminated coastal sediments. The distribution of silver in the surface sediments reflects the loadings of silver and transport processes during the last 100 years. Concentrations of silver in the surficial sediments are highest in Boston Harbor (in excess of 4 parts per million (ppm) in some areas) and decrease offshore to background concentrations of 0.14–0.18 ppm to the east of Stellwagen Bank in the Gulf of Maine (Ravizza and Bothner, 1996) (fig. 6.6). Offshore of Boston in western Massachusetts Bay, silver concentrations vary from 0.04 ppm in areas of coarse-grained sediments to about 0.7 ppm in a small area of fine-grained sediments (long-term sampling site 3, figs. 2.5B and 7.3A). Silver concentrations are about 0.5 ppm in Cape Cod Bay and 0.20 ppm in Stellwagen Basin; this distribution suggests southeasterly (alongshore) and easterly (offshore) transport to these depositional sites from Boston Harbor.

Simulations of the transport of fine-grained material from Boston Harbor and from the new outfall site during idealized northeast storm conditions show transport into Cape Cod Bay and Stellwagen Basin. Under winds from a direction of 12º, material from Boston Harbor is carried in a narrow band along the coast southeastward toward Cape Cod Bay; some material is carried northward by bottom currents opposite to the direction of the wind, reaching Stellwagen Basin (fig. 6.7A). Material from the new outfall site travels southeastward, then offshore into Stellwagen Basin. After 10 storms, some material from both sites escapes Massachusetts Bay into the Gulf of Maine. Under winds from a direction of 50º, material from Boston Harbor moves southeastward, offshore into Stellwagen Basin, and into the Gulf of Maine; transport to Cape Cod Bay is weaker than under winds from the north (fig. 6.7B). Material introduced at the new outfall site follows a similar path, but does not enter Cape Cod Bay. Even after one storm, some material escapes to the north of Stellwagen Bank and into the western Gulf of Maine.

The modeled transport pathways of sediments from Boston Harbor are consistent with Boston being the long-term source of silver found in the surficial sediments in Cape Cod Bay and Stellwagen Basin. Storms with winds from 0º to about 60º cause southeastward transport toward Cape Cod Bay in a nearshore band along the western side of Massachusetts Bay, and northward into Stellwagen Basin. Storms with winds from 60º or greater cause near-bottom flow directly offshore into Stellwagen Basin (fig. 6.4). Physical or biological vertical mixing of sediments deposited on the sea floor after each storm would bury the sediments in the sediment column and make them less available for resuspension by subsequent storms; this mixing would efficiently sequester the silver in the bottom sediments. The higher silver concentrations in Cape Cod Bay relative to Stellwagen Basin are consistent with alongshore transport of silver-laden sediments toward Cape Cod Bay caused by winds from the north and northeast. However, the observed distribution of silver in the surficial sediments reflects the cumulative transport by a sequence of storms with a variety of wave and wind characteristics, and the spatial and temporal history of the discharge of silver into the Massachusetts Bay system during the last 100 years or so. The ultimate distribution and fate of silver is also influenced by biological mixing (bioturbation; Section 9) and by geochemical cycling (Section 10) in the top several centimeters of the sediment column.

The northeast storms used in these model simulations are some of the largest observed in the 16-year wave record from 1990 through 2005. Storms with weaker winds would drive similar circulation patterns, but the waves, responsible for most of the sediment resuspension, also would be weaker and thus resuspend sediments less frequently in Stellwagen Basin (too deep) and Cape Cod Bay (sheltered from the east). Thus, even small northeast storms would transport sediment along the shallower portions of the transport pathways to depositional sites, but only from water depths at which the waves are strong enough to resuspend sediments.

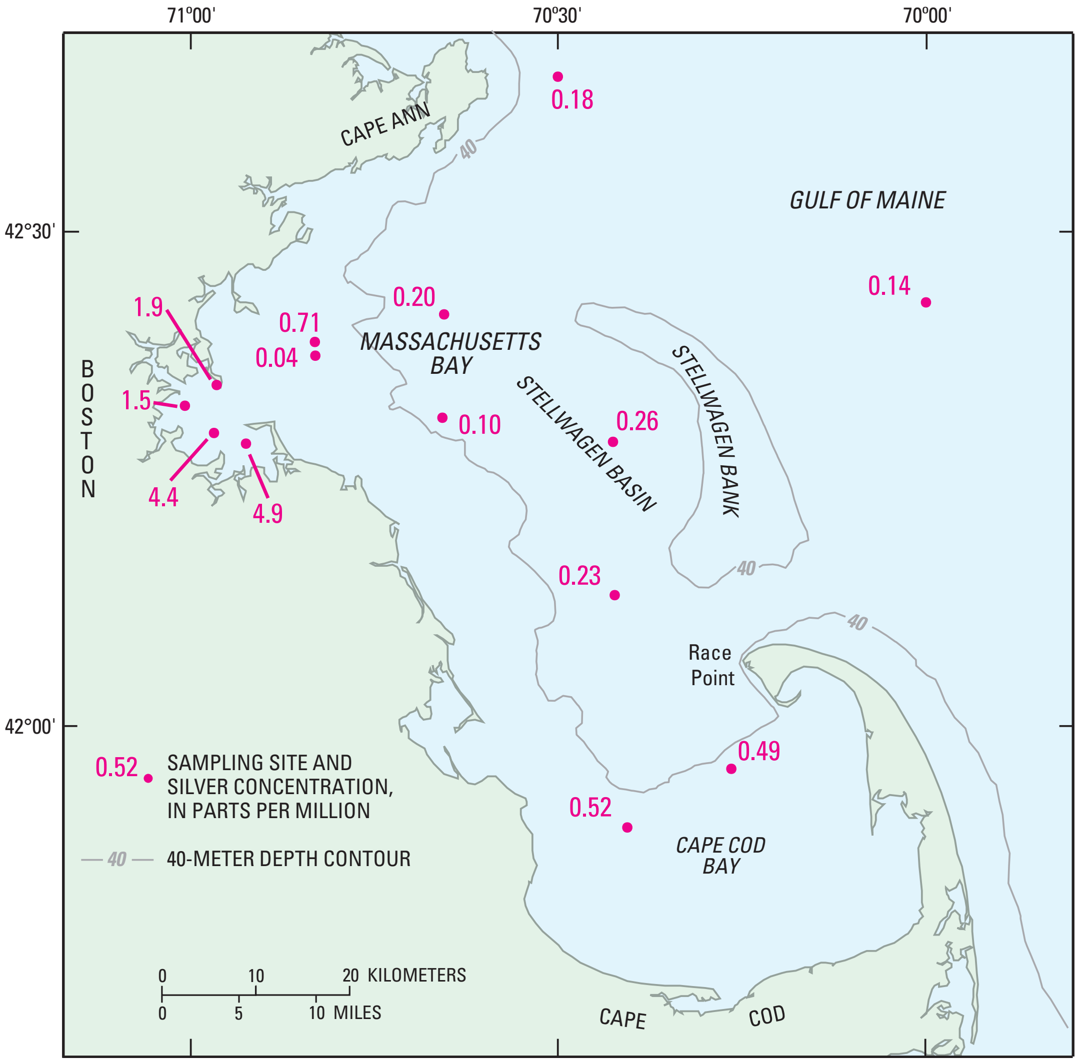

Figure 6.6. Concentration of silver in surface sediments in parts per million (ppm). Silver has accumulated in regions of fine-grained sediments in Boston Harbor, in small areas of fine-grained sediments offshore of Boston, and in Cape Cod Bay and Stellwagen Basin. (From Ravizza and Bothner, 1996.)

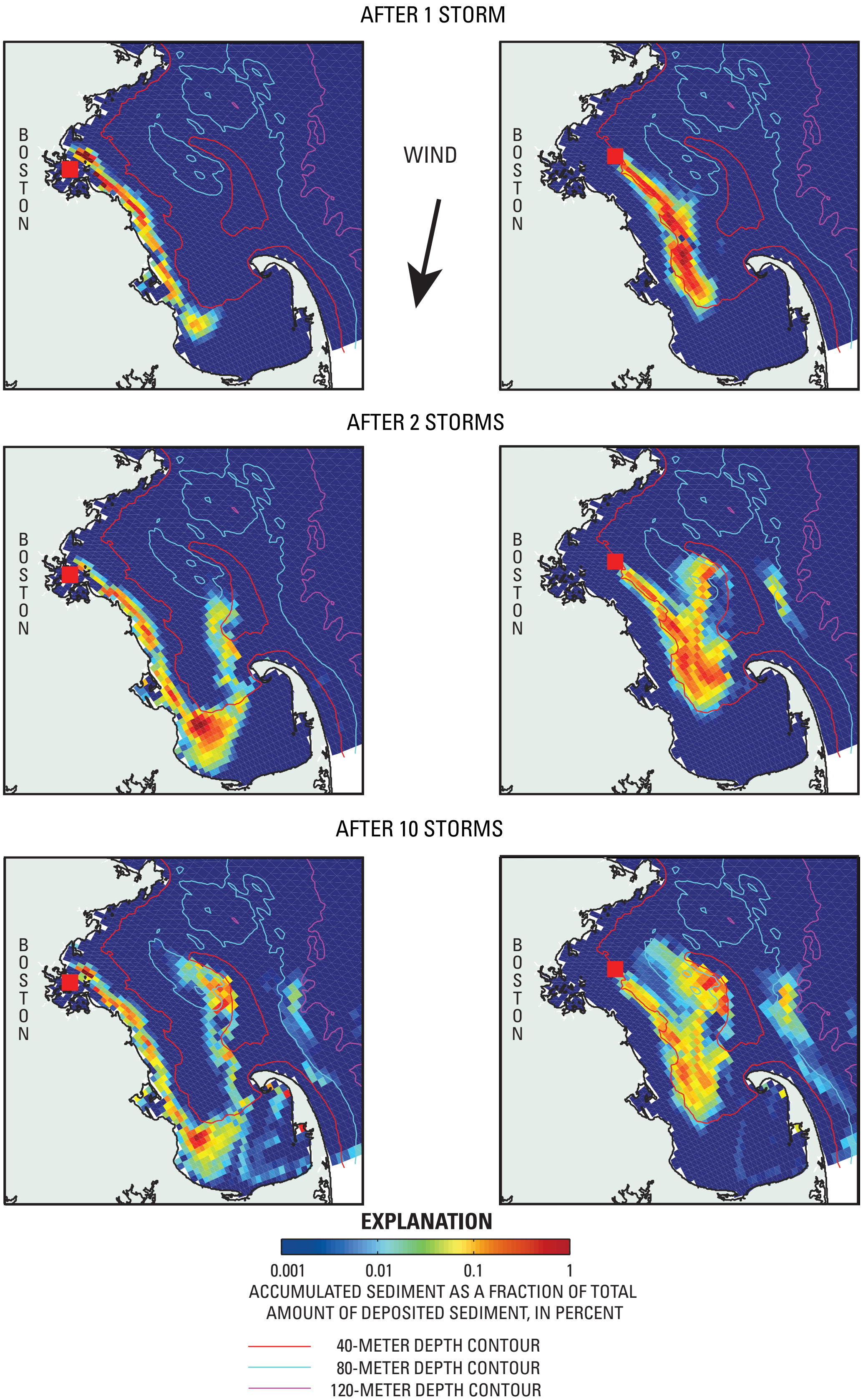

Figure 6.7 ***(A).*** Predicted accumulation of sediment on the sea floor transported from sites (indicated by squares) in Boston Harbor (left panel) and western Massachusetts Bay (right panel) after 1 (top), 2 (middle), and 10 (bottom) storms caused by waves and winds modeled after the March 1997 storm (wind from a direction of 12º). The colors show the accumulation of sediment transported from the respective site as a percentage of the total amount of sediment deposited on the sea floor in Massachusetts Bay (excluding sediment deposited in Boston Harbor) since the beginning of the simulation. The accumulation is shown at maximum ebb-tidal current. After one storm, sediment from both sites travels southeastward toward Cape Cod Bay. After 10 storms, sediment from Boston Harbor has accumulated in Cape Cod Bay, and sediment from both sites has accumulated in Stellwagen Basin. This pattern of accumulation is consistent with Boston Harbor being the source of silver found in the sediments of Cape Cod Bay and Stellwagen Basin (fig. 6.6).

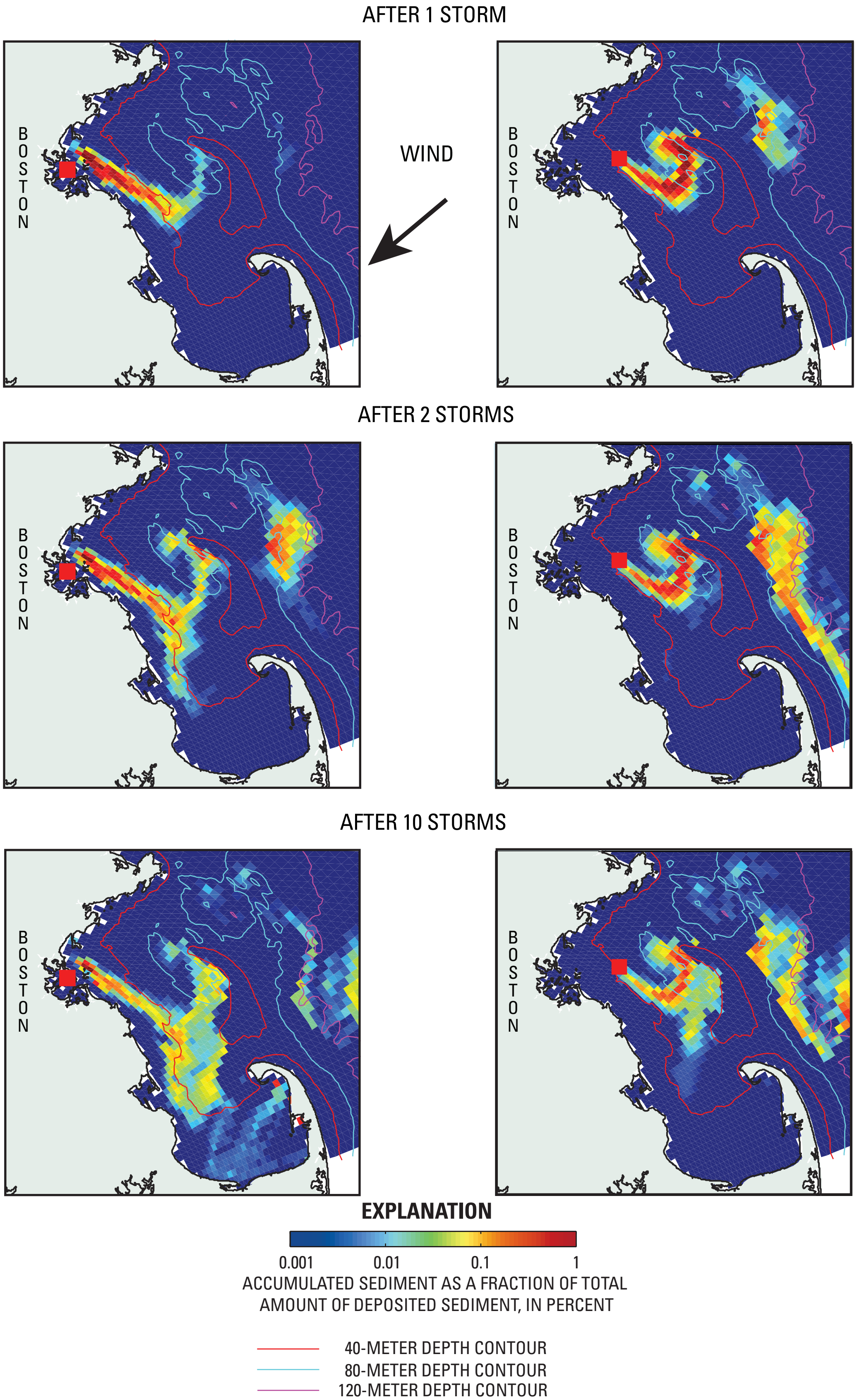

Figure 6.7 ***(B).*** Predicted accumulation of sediment on the sea floor transported from sites (indicated by red squares) in Boston Harbor (left panel) and in western Massachusetts Bay (right panel) after 1 (top), 2 (middle), and 10 (bottom) storms caused by waves and winds modeled after the December 1992 storm (wind from a direction of 50°). The colors show the accumulation of sediment transported from the respective site as a percentage of the total amount of sediment deposited on the sea floor in Massachusetts Bay (excluding sediment deposited in Boston Harbor) since the beginning of the simulation. The accumulation is shown at maximum ebb-tidal current. After 10 storms, sediment from both sites has accumulated in Stellwagen Basin. This pattern of accumulation is consistent with Boston Harbor being the source of silver found in the sediments of Stellwagen Basin (fig. 6.6).