4. PHYSICAL AND BIOLOGICAL OCEANOGRAPHY OF MASSACHUSETTS BAY

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4.1 General characteristics

The transport of effluent discharged from the outfall is determined by local mixing and by the general circulation within Massachusetts Bay, which is illustrated by Figure 4-1 (Lermusiaux et al. 2001). There are a number of different possible trajectories of the flow, depending on the density distribution in the system and the winds. The residence time of the bay varies with the inflow from the Gulf, and Cape Cod Bay is at times somewhat isolated from Massachusetts Bay.

Moorings deployed by the USGS at the outfall site and at Scituate show these different trajectories. For example, in 1999 the residual flow was to the south in March and to the north in May as shown in Figure 4-2 (Butman et al. 2002.)

The bay is stratified from about April through October, which leads to trapping of the effluent plume. Density- and wind-driven flow, described in more detail below, determine the near-field transport of effluent.

Figure 4-1  Summary of circulation within Massachusetts Bay (Lermusiaux et al. 2001.)
Massachusetts Bay wind stress, and currents at 5 meters below the surface (mbs) at outfall site (USGS mooring Site A) and off Scituate (USGS mooring Site B), during 1999 (Butman et al. 2002.)

4.2 Influence of the Gulf of Maine

Circulation, water properties, and consequently, the biology of Massachusetts and Cape Cod bays can be affected by the larger pattern of water flow in the Gulf of Maine (Figure 4-3.) The eastern Maine coastal current usually flows southwestward along the coast of Maine and New Hampshire and may enter Massachusetts Bay south of Cape Ann, exiting the Bays north of Race Point at the tip of Cape Cod. During the spring, when fresh water enters from the north and northerly winds are prevalent, the transport often follows the counterclockwise path in Figure 4-1, around the perimeter of Massachusetts Bay, into Cape Cod Bay and out around Race Point. In late spring and summer, Cape Cod Bay becomes isolated from this circulation.

The winds strongly influence the direction of circulation and the connectivity between the Gulf of Maine and the Bay. The optimal conditions for input of Gulf of Maine waters are winds from the northeast, combined with significant freshwater inflow from the Gulf. Winds from the south impede the surface water inflow, although they cause upwelling, which allows deep waters to enter from the Gulf.
4.3 Vertical structure

The Merrimack River and rivers further north in the Gulf of Maine provide most of the freshwater inflow (Manohar-Maharaj and Beardsley, 1973). Although they don’t empty directly into Massachusetts Bay, their flow is much greater than that of the Charles River and other Massachusetts Bay rivers (Figure 4-4). The spring freshet results in salinity stratification in early April. Surface warming as the spring progresses enhances the stratification (Geyer et al. 1992). During the summer there is a strong and persistent pycnocline throughout most of Massachusetts and Cape Cod bays, occasionally punctuated by storm mixing events. Stratified conditions continue through October in most years, sometimes later.
Figure 4-4  Merrimack and Charles River discharge, 1990-2002 (red/thicker line shows 3-month moving average.) Note difference in scale between Merrimack and Charles.
The waters of Massachusetts Bay become stratified during the spring freshet in April, due to the input of fresh water from the rivers of the Gulf of Maine, and in western Massachusetts Bay from the input of the Charles River. As the surface waters warm up in May and June, temperature stratification dominates over that due to the freshwater input. The waters remain stratified until late October or early November, when surface cooling and wind stress cause the water column to become vertically mixed. Figures 4-6 through 4-8 show the seasonal progression of temperature, salinity and density across northern Massachusetts Bay for the year 2000. The density distribution is determined by both temperature and salinity.

**Figure 4-5**  Nearfield surface and bottom water temperature (top panel) and salinity (bottom panel), 1992-2002
(surface measurements are the upper blue line for temperature and the lower blue line for salinity.)
Figure 4-6  Temperature cross-sections from Boston Harbor to the Gulf of Maine, through the outfall zone.

The top panel shows conditions in April, at the beginning of seasonal stratification. The stratification increases in June, and reaches its maximum in August. In October, surface temperature is decreasing, but the bottom water is continuing to warm. Temperature contours in °C.
Figure 4-7 Salinity cross-sections from Boston Harbor to the Gulf of Maine, through the outfall zone.

The top panel shows conditions in April, when freshwater inputs are beginning to establish vertical and horizontal salinity gradients. The largest gradients occur during the June survey, which follows a large freshwater inflow from the Charles River. Significant salinity gradients persist through August. Salinity contours in PSU.
Figure 4-8  Density variations across Massachusetts Bay during four surveys in 2000. Stratification is contributed mostly by salinity during the April survey. The maximum stratification occurs in August, with contributions from both temperature and salinity. Density as sigma-τ.
4.4 Short time scales

Tides

The large tides of the Gulf of Maine affect the open waters of the bays through tidal mixing (for example, over Stellwagen Bank) and the production of internal tides (Butman et al. 1988, Geyer et al. 1992, Geyer and Ledwell 1997.)

The extent of horizontal exchange is illustrated by Figure 4-9, a set of progressive vector diagrams provided by Soupy Alexander and Brad Butman at USGS. The plots indicate 1-day trajectories over a one-month period, at near-surface and deep water levels, based on analysis of current meter data. The trajectories include the effects of tides, which cause east-west excursions of several kilometers, as well as motions due to winds and other factors. The key point is that although the long-term average, net velocity is small at the outfall site, there is considerable dispersion, which causes water parcels to be exchanged freely between the outfall site and other parts of the Bay.

The largest displacements in Fig 4-9 are in surface waters in summer. The vertical density gradient present in summer allows surface waters to slip relative to bottom waters and thus move more readily in response to wind and tide.

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Note that the currents were measured only at the USGS mooring near the outfall site; progressive vector diagrams would only represent real water parcel trajectories if currents were uniform throughout western Massachusetts Bay. Nevertheless this data presentation is a useful visualization of the variability of the flow at the outfall site.
Figure 4-9 Progressive vector diagrams of currents near outfall site.

Trajectories illustrate 24-hour variation in currents from January 2000 (left) and July 2000 (right), near the surface (top panels) and near-bottom (bottom panels.) Currents were measured with the Acoustic Doppler Current Profiler on the USGS mooring. Figures courtesy of Soupy Alexander and Brad Butman, USGS.
Wind

Wind-induced upwelling and downwelling causes large variations in the water properties at the outfall site, by advecting the waters on- and offshore. Persistent, strong southerly or southwesterly winds in summer lead to upwelling. Upwelling causes a decrease in both surface and bottom water temperature, but most notably the surface water. Downwelling causes a significant increase in bottom water temperature. Upwelling and downwelling have some influence on vertical exchange, but their main influence is the horizontal advection of gradients. Figures 4-5 and 4-6 above shows the variability in bottom water temperatures.

Wind effects also include temporary destratification of the water column by large summer storms (for example, Hurricane Bob in 1990.) A stormy early autumn can also lead to early fall turnover.

4.5 Hydrodynamic model results

The ECOMsi hydrodynamic model has been applied to Massachusetts Bay (Signell et al. 1996.) It reproduces the physical conditions in the bays well, provided the boundary conditions at the open ocean boundary and the sea-surface heat flux are appropriately modeled or measured (Signell et al. 1996, 2000; HydroQual 2002; Figures 4-10 and 4-11.) The model reproduces the southward flow along the coast that is common in spring, as well as the summer/fall reversal of circulation (Jiang et al. 2003, see Figure 4-12.)
Figure 4-10  Observed and modeled salinity and temperature, and observed winds at the Boston Buoy, June 15-July 15, 1998 (HydroQual 2002.)
Figure 4-11  Observed and modeled tidal currents, summer 1992  (Signell et al. 2000.)
Figure 4-12  Modeled surface temperature and circulation patterns in spring 1999 (top panel) and summer 1999 (bottom panel) showing northward flow along the coast (figure courtesy Mingshun Jiang, UMass/Boston.)
Color shows surface temperature (4-8 C in spring, 10-20 C in summer).
4.6 Effluent dilution and dispersion

The impact of the effluent is minimized by effective dilution. A 2-km long diffuser with 271 ports disperses the effluent into the 30 m deep waters in the Bay, where the effluent mixes rapidly with large volumes of seawater to achieve very low concentrations of any contaminants that remain after secondary treatment. The initial dilution of the effluent is about 100:1. The results of a dye study and other data documenting the initial dilution are presented in Section 5.

In the winter, the effluent plume reaches the surface, while during the stratified season it is trapped below the pycnocline, in the bottom 15-20 m of the water column.

After initial dilution the effluent is dispersed more gradually throughout western Massachusetts Bay. There is essentially no mean flow at the outfall location; bottom currents of around 6 cm/s are very variable in direction (Butman et al. 2002.) The primary temporal and spatial scales of variability near the outfall are those of the tides and of local weather patterns. After initial dilution, drifter and model studies indicate that effluent constituents may move toward the shore, or offshore where they are incorporated into the general circulation of the bays (Figure 4-13.)

Figure 4-13  Paths of drifters released in May 1990 illustrating the variability of the surface currents in Massachusetts Bay (Geyer et al. 1992.) Time represented by each track varies from two days (for drifters going ashore in Boston Harbor or Scituate) to three weeks (for drifters entering Cape Cod Bay.)
4.7 The Massachusetts Bay ecosystem seasonal cycle

Although Massachusetts and Cape Cod Bays generally follow the annual cycle typical for coastal waters, monitoring has shown that wind, regional conditions, and other factors greatly influence the pattern. Waters are well mixed and nutrient levels are high during November through April. As light levels increase in early spring, there is often a bloom of phytoplankton; spring blooms may occur earlier than the onset of stratification, or not at all. During the years in which there are spring blooms, they begin in the shallower waters of Cape Cod Bay. Blooms in deeper waters begin two to three weeks later. Spring phytoplankton blooms are typically followed by an increase in zooplankton abundance. The endangered right whale may typically visit Cape Cod Bay to feed during December through May (http://www.coastalstudies.org/research/right.htm.)

Throughout late spring and summer, stratification effectively separates the surface and bottom waters, preventing replenishment of nutrients to the surface and of oxygen to the bottom. Phytoplankton in the surface waters deplete the available nutrients and then undergo senescence. Phytoplankton abundance is also depleted by grazing. Oxygen levels remain high in the surface waters throughout the year, but oxygen levels decrease in the bottom waters due to respiration of sinking particulate matter.

Respiration consumes dissolved oxygen and the levels decline in bottom water decrease though the autumn (September-October) until mixing in late fall replenishes bottom oxygen levels. Advection also affects bottom DO concentrations. Nearfield DO tends to be lowest when the bottom waters are warm and salty, possibly reflecting advection from the Gulf of Maine of low DO waters having those temperature and salinity characteristics (Libby et al. 2000.)

In the fall, cooling surface waters and strong winds promote mixing of the water column. Oxygen is replenished in the bottom waters, and nutrients brought to the surface stimulate a fall phytoplankton bloom. The fall bloom is often stronger than the spring bloom. Typically, fall blooms end in the early winter, when declining light levels limit photosynthesis. Plankton die and decay, replenishing nutrients in the water column.

Warmer years appear to have weaker spring blooms as described in Section 5. Stronger stratification results in more depletion of surface nutrients in summer; this may lead to stronger fall blooms since more nutrients are available after turnover (Jiang et al. 2003.) Cool years such as 2001 tend to have lower phytoplankton and zooplankton abundance (Jiang et al. 2003.)

4.8 Spatial variability

The spatial variability in biological parameters is driven by bathymetry and proximity to the open ocean boundary. Shallow enclosed bays such as Boston Harbor have higher levels of nutrients and chlorophyll than do open waters. Stellwagen Bank is highly productive because strong tidal currents over the bank mix nutrients throughout the water column. Likewise, southeastern Cape Cod Bay tends to have higher chlorophyll (Figure 4-15) because of its shallow depth. More detailed results on spatial variation in biological parameters are given in Section 5.
4.9 Water quality model results

A three-dimensional water quality model of the bays has been constructed (HydroQual and Normandeau, 1995, HydroQual 2000, 2001, 2002, Jiang et al. 2003.) This model reproduces the general seasonal cycle and spatial variability of nutrients, oxygen, and chlorophyll (Figures 4-16 and 4-17). Model results indicate that the values of these parameters in western Massachusetts Bay and in Cape Cod Bay are quite sensitive to the values at the boundary with the Gulf of Maine.
Figure 4-15  Comparison of Bays Eutrophication Model results and data for various water quality parameters in nearfield, 1993 (HydroQual 2001.)
Figure 4-16  Comparison of Bays Eutrophication Model results and data for chlorophyll for six locations, 1993 (HydroQual 2001.)
4.10 Regional scale biology

Variations in the biology and physics in the Gulf of Maine have a strong effect on the Massachusetts Bay/Cape Cod Bay system. The exchange with the boundary – most importantly, whether the Maine coastal current enters Massachusetts Bay or stays outside Stellwagen Bank – determines nutrient and oxygen levels in the interior of the bay, and the residence times of water in Massachusetts Bay and Cape Cod Bay. Nuisance algae such as *Alexandrium fundyense/tamarense* can be transported into the bay from the Gulf of Maine.

The open ocean boundary, because of the large transport of water across it, is the major source of nutrients to the bays. For example, HydroQual (2000) estimated that in 1992 the Gulf of Maine contributed 92% of the total nitrogen entering the bays, with MWRA effluent contributing 3% and other sources (mostly atmospheric) contributing 5%.

Dissolved oxygen near the outfall is highly correlated with oxygen levels in deep water near the boundary. The effect of the Gulf of Maine on the dissolved oxygen and nutrient levels is described in more detail in Section 5.

Nuisance blooms can be linked to the larger circulation in the Gulf of Maine: for example, winds, currents and spring runoff during May can determine whether red tide enters Massachusetts Bay or is transported out to sea (Anderson, 1997, Anderson *et al.* 2002, Figure 4-18.)

As described in more detail in section 5, phytoplankton and zooplankton species composition and abundance tend to vary on a baywide or regional scale. Except in Boston Harbor, species observed are typical of the open waters of the northwest Atlantic Ocean. Some have predictable seasonal cycles, while others (such as certain nuisance species) appear only intermittently.
Depending on winds during an offshore bloom, populations of *Alexandrium* may either be transported into the Bay by winds from the northeast, also referred to as downwelling-favorable conditions.
References


Signell, R.P., Jenter, H.L. and Blumberg, A.F. (2000). Predicting the physical effects of relocating Boston's sewage outfall. Estuarine, Coastal and Shelf Science, special issue on Visualisation in Marine Science, January 2000, and

http://smig.usgs.gov/SMIG/features_0999/bharbor_inline.html#model