2. WATER COLUMN FEATURES

As stated previously, Massachusetts is situated between two major biogeographic regions. The waters of Massachusetts north of Cape Cod are influenced by the relatively cold Gulf of Maine currents, while the waters to the south and east of Cape Cod are influenced by the relatively warmer waters from the Gulf Stream and the Southern New England-New York Bight. In addition, the waters to the north of Cape Cod are deeper and have different landside influences than the waters south of Cape Cod. Both areas however, are similarly affected by regional climatological changes that result in seasonal shifts in temperature, dissolved oxygen, stratification, and primary productivity.

The sections below describe the general water column features for these two major waterbody regions in the planning area. It should be noted that there has not been a systematic effort to describe water column features throughout the planning area. What is known is the result of discrete projects that may or may not represent the planning area as a whole. For example, much of what is known about Massachusetts Bay is the result of work done by the Massachusetts Water Resources Authority (MWRA) and its partners to determine if the MWRA sewage outfall is affecting the bay. While the MWRA data set is fairly rich where samples are taken, the sampling effort does not include waters north of Cape Ann. On the other hand, relatively less is known about the waters to the south of Cape Cod and what is known is being driven by institutional research or infrastructure projects such as Cape Wind. The paucity of data in some rather large portions of the planning area speaks to the need for a more coordinated approach to understanding the Commonwealth's ocean waters.

NORTH OF CAPE COD

Massachusetts and Cape Cod Bays are both connected to the larger Gulf of Maine system via the Maine Coastal Current (MCC). The so-called western branch of the MCC or WMCC (Lynch *et al.* 1997), derives in part from water flowing east to west over the Scotian Shelf, but also from the major rivers in the Gulf of Maine—the St. John, Penobscot, Kennebec, Androscoggin, Saco, and Merrimack (Figure 2.1). The WMCC splits south of Cape Ann where one branch flows east of Stellwagen Bank, splitting again near Nantucket where one branch exits the Gulf of Maine through the Great South Channel and the other branch circles clockwise around George's Bank (Geyer *et al.* 1992). The part of the WMCC that enters Massachusetts Bay forms a counterclockwise current, though its direction and intensity may vary seasonally. In addition, there are many smaller currents in Massachusetts Bay that branch off of and may run opposite to the main counterclockwise current. The branch of the WMCC that enters Massachusetts Bay flows south through most of the bay, then exits north of Race Point in Provincetown. Further south, the currents in Cape Cod Bay are fairly weak, except during strong freshwater run-off periods when the current from Massachusetts Bay flows along the southern coast to Cape Cod Bay, expanding its counterclockwise gyre, before exiting past Race Point.

Owing to the shape of the Gulf of Maine, the waters of Massachusetts Bay and Cape Cod Bay are macrotidal, experiencing a semidiurnal tidal range of up to 4.1 m (13.4 ft). The maximum depth is 89 m (292 ft), found in Stellwagen Basin, while the average depth is 30 m (98 ft). Changing tides and the flow of freshwater from the large rivers to the north generate the currents in the Gulf of Maine, but they can also be influenced by winds, especially out of the northwest or northeast. Although most of the planning area north of the Cape is in open, unrestricted water with currents less than 1.8 kilometers per hour (km/hr or roughly 1 knot), at the mouth of Boston Harbor currents can get as high as 2.6 km/hr (1.4 knots) during the full and new moon cycles (White and White 2007). In addition, currents greater than 1.8 km/hr (1 knot) can be found off of Cape Anne and the tip of Cape Cod. The movement of water in Massachusetts and Cape Cod Bays has been modeled successfully by several researchers. A recent model is maintained by professor Mingshun Jiang of UMass Boston and can be queried for surface temperature, salinity, and currents (http://www.harbor1.umb.edu/forecast/model.html).

Insert figure of currents "Circulation in GOM" reference Pettigrew et al. 2005 for figure.

SOUTH OF CAPE COD

The waters south of Cape Cod include Buzzards Bay, Vineyard Sound, Nantucket Sound, and the Great South Channel (Figure 2.2). Lacking the Gulf of Maine's large riverine inputs, the waters of Buzzards Bay and the Sounds are largely influenced by tidal currents, while waters to the east of Cape Cod are influenced by both the tides and the Gulf of Maine waters flowing around Provincetown. In contrast to the waters to the north, waters to the south of Cape Cod are microtidal, dominated by semidiurnal tide-generated currents, and influenced by southwesterly winds. The currents within Buzzards Bay are less than 1.8 km/hr (1 knot), except at the mouth, between Cuttyhunk Island and Westport, where currents can be as great as 2.6 km/hr (1.4 knots) on the flood tide. In Vineyard Sound, maximum currents are 7.2 km/hr (3.9 knots), while in the Nantucket Sound area the currents in Muskeget Channel and Pollock Rip Channel southeast of Monomoy Island are 8.1 km/hr (4.4 knots) and 4.4 km/hr (2.4 knots), respectively (White and White 2007).

The maximum tidal range of the planning waters south of Cape Cod is 2.0 m (6.4 ft). The maximum depth is 65 m (213 ft) and due to significant shoaling, especially within the sounds, the average depth is only 14 m (46 ft). An effort to model Nantucket and Vineyard Sounds is currently underway by researchers from Wood Hole Oceanographic Institute and UMass Dartmouth.

Table 2.1. Major oceanographic characteristics.

	North of Cape Cod	South of Cape Cod
Ocean Surface Area	2,697 km^2 (1,041 $miles^2$)	2,852 km^2 (1,101 $miles^2$)
Maximum Depth	89 m (292 ft)	65 m (213 ft)
Average Depth	30 m (98 ft)	14 m (46 ft)
Tidal Range	4.1 m (13.4 ft)	2.0 m (6.4 ft)

UPWELLING, FRONTS, AND WAVES

Upwelling is a hydrodynamic phenomenon whereby sustained winds push warm, nutrient poor surface waters offshore where they then sink and induce the upward motion of deeper, cooler, and nutrient rich waters along the adjacent shoreline. Upwelling results in periods of increased primary productivity in the ocean due to this advection of nutrients into the photic zone and the resulting blooms of phytoplankton.

Oceanic fronts are areas where two water masses meet. The sharp gradients in temperature or salinity that define a front result in the upwelling of nutrients that promote primary productivity. Like wind-driven upwelling areas, fronts are typically sites of increased primary and secondary productivity and concentrate filter feeding organisms such as clupeid fishes (*e.g.*, Atlantic herring) and baleen whales. Because these oceanographic features can be used as predictive tools to find concentrations of marine mammals, fish, and phytoplankton (Friedland *et al.* 2006), oceanic fronts may be part of important trophic interactions (Schick *et al.* 2004). However, the location and duration of fronts are not very well understood in the planning area.

Surface waves are generated by winds passing over the ocean. Their height is dependent upon the velocity of air moving above the ocean, the fetch over which it moves, and the density of the water. From 2001 to 2008, the Massachusetts Bay "A" buoy (42° 31' 21" N, 70° 33' 57" W) recorded an average wave height of 1.0 m (3.3 ft), ranging from 0.04 m to 9.95 m (0.13 to 32.6 ft). Similarly, the Boston Harbor Buoy 44013 (42° 21' 00" N, 70° 41' 24" W) recorded an average wave height of 0.9 m (3.0 ft), ranging from 0.2 m to 8.5 m (0.7 to 28 ft) (GoMOOS 2008). Wave height data are not available for the planning area north of Cape Ann or South of Cape Cod.

Internal waves are sub-surface, oceanic waves that propagate either obliquely when the ocean is uniformly stratified or horizontally when the ocean's stratification is confined to discrete, narrow bands. The momentum and energy distributed by internal waves can thus be used to de-stratify, or mix the ocean waters and its associated sediments, nutrients, and plankton. This mixing may be important to sustaining deep-water communities that are otherwise sequestered from the productivity at the surface by persistent stratification. Researchers speculate that internal waves may also be important in large-scale, deep ocean circulation due to the transfer of heat from the surface (Zimmerman *et al.* 2008).

RIVERINE INPUTS

Rivers carry freshwater, nutrients, and pollutants throughout their watersheds, from uplands to coastal wetlands and the ocean. The coastal watersheds that drain to the planning area are the Merrimack, Parker, Ipswich, North Coastal, Mystic, Charles, Neponset, Weymouth/Weir, South Coastal, Cape Cod Bay, Cape Cod (draining the south and east portions of the Cape), and Buzzards Bay.

The Merrimack River is the largest river in Massachusetts with a ten-year average flow of 245 cubic meters per second (cms) or 8,746 cubic feet per second (cfs). During the spring snowmelt and runoff, flows may be up to 616 cms (22,000 cfs). The greatest runoff event in the last decade occurred in May 2006, when the Merrimack discharged at a rate greater than 2,520 cms (90,000 cfs) (USGS 2008). Other than the Merrimack, there are no large rivers entering Massachusetts Bay. The next largest River, the Charles, has an average discharge of only 14 cms (487 cfs). Nor are there large rivers draining to Cape Cod Bay, the sounds, or Buzzards Bay. For comparison, there are several large rivers north of Massachusetts that influence the Gulf of Maine and thus the planning area, including the St. John, Penobscot, Kennebec, Androscoggin, and Saco rivers. Interestingly, the second largest freshwater input to the planning area is the MWRA outfall, which discharges treated sewage and stormwater from the metropolitan Boston area at a rate of 16 cms (565 cfs) to a diffuser outfall 15.3 km (9.5 miles) from shore.

SEA TEMPERATURE

As noted above, Cape Cod forms a physical boundary between two major ocean regions. It is not surprising then that distinctly different temperatures are found north and south of this division. According to the Gulf of Maine Ocean Observing System (GoMOOS), the average surface temperature at the Massachusetts Bay A buoy from 2001 to 2008 was 10.8 C (51.4 F) while the average surface temperature at the National Data Buoy Center's "BUZM3" buoy at the mouth of Buzzards Bay (41° 24' 00" N, 71° 01' 48" W) over the same time period was almost two degrees warmer at 12.6 C (54.6 F). Further details on temperature in Massachusetts and Buzzards Bays can be found in Table 2.

Table 2.2. Sea temperatures in the Massachusetts ocean planning area (courtesy of GoMOOS 2008).

	Max temp C (F)	Min temp C (F)	Average temp C (F)
Massachusetts Bay Surface	23.9 (74)	1.1 (34)	10.8 (51.4)
Massachusetts Bay -50 m	13.4 (56.1)	1.9 (35.4)	6.3 (43.4)
Buzzards Bay Surface	23.2 (73.8)	2.1 (35.8)	12.6 (54.6)

SEASONAL CHANGES

Due to the location of Massachusetts in temperate latitudes, the planning area experiences seasonal shifts in temperature. As noted above, sea surface temperature varies up to 22 C (30 F) seasonally. The most recent seven years of air temperature data collected at the Boston A Buoy indicate that average air temperature was 10 C (50 F), and ranged between -18.9 C and 26.7 C (-2 F and 80 F; GoMOOS 2008). In summer, the air mass above the planning area waters is generally warmer than the ocean. Heat is transferred from the air to the upper layer of the ocean. As this upper layer of the ocean becomes significantly warmer than the water beneath it, a definitive boundary called the thermocline forms where the transition from relatively warm water to relatively cold water is abrupt. This boundary persists throughout the summer months, then weakens and disappears in the fall.

Stratification is important in that it allows phytoplankton to consume and deplete all of the nutrients in the upper layer, which in turn can not be replenished until the stratification is broken up. Nutrients can also arrive via freshwater runoff because it is less dense than ocean waters and moves along the ocean's surface, but this is relatively less common in summer months. Thus seasonal stratification influences primary productivity by restricting the availability of nutrients. Stratification also affects dissolved oxygen levels as deeper waters below a thermocline have less opportunity to mix with oxygen rich waters at the surface. In Massachusetts Bay dissolved oxygen levels are highest between January and March (9-12 mg/l or parts per million (ppm)), decrease steadily to 6-8 mg/l (ppm) between September and November, and then begin increasing again after stratification breaks up (Werme *et al.* 2008). Wind, waves, upwelling, and the seasonal decrease in ocean surface temperature that arrives typically in October or November all contribute to destratification.

WATER QUALITY

Water quality is a measure of the physical and chemical characteristics of a waterbody that influence its appearance, its mobility, and its ability to support aquatic life and human activities. The water quality parameters listed below (bacteria, chlorophyll a, dissolved oxygen, harmful algae blooms, nutrients, pH, salinity, Secchi depth, sound, and total suspended solids) are all known to change as the result of human use and management decisions in near shore areas. Some of these changes may increase or decrease water quality parameters to levels that are harmful to aquatic life and human activities. As the ocean planning process begins to unfold, it will be necessary to monitor these same parameters to ensure that the management decisions made in the planning area, away from shore, and in the upland watersheds, do not degrade marine habitats and aversely affect marine communities.

Bacteria

The planning area is adjacent to several wastewater facilities that discharge bacteria to Commonwealth waters. Most bacteria sampling to date is off of beaches and over shellfish beds that are outside the planning area, however the MWRA does analyze water samples collected from throughout Massachusetts Bay for bacteria (MWRA 2008). All samples collected in 2007 had < 1 fecal coliform colony per 100 ml (0.03 gallon) and < 10 enterococcus colonies per 100 ml (0.03 gallon), suggesting that the planning area waters are relatively free of the bacteria that are indicators of pathogen contamination. There is not any systematic sampling for bacteria in the planning area south of Cape Cod.

Chlorophyll a

Chlorophyll a is a pigment found in plants that allows them to photosynthesize. Chlorophyll a levels in a water column are used as indicators of the presence of phytoplankton. When phytoplankton densities increase to high levels (*i.e.*, during a bloom) chlorophyll a levels will also be high. In the planning area, spring and fall blooms are annual events. Data from MWRA monitoring in Massachusetts Bay (Werme *et al.* 2008) indicate that during the March/April bloom, chlorophyll a levels average just about 2.5 mg/l (part per million or ppm). Levels decrease to less than 2 mg/l (ppm) and then increase again in September through November to about 4 mg/l (ppm). In Nantucket Sound, data collected in 2006 and 2007 by the Nantucket Soundkeeper (2008) indicate that summer time levels of chlorophyll a average 3.6 mg/l (ppm) at the surface and 3.9 mg/l (ppm) at the bottom.

Dissolved Oxygen

Dissolved oxygen is a measure of the amount of oxygen dissolved in a water column and thus the amount available for plants and animals to perform the necessary function of respiration (the oxidation of sugars to create energy). In Massachusetts Bay, Werme *et al.* (2008) report that dissolved oxygen is lowest at around 7 mg/l (ppm) in October, increases steadily to about 11 mg/l (ppm) in March/April and then decreases steadily through the summer months. In the summers of 2006 and 2007, the average dissolved oxygen level in Nantucket Sound was greater than 7 mg/l (ppm) (Nantucket Soundkeeper 2008). Dissolved oxygen levels in the nearshore environment, which is outside of the ocean planning area, are typically lower than in Massachusetts Bay and Nantucket Sound, largely because of the nearshore's proximity to sources of anthropogenic nitrogen and its relatively lower flushing and mixing characteristics.

The Massachusetts Water Quality Standards (314 CMR 4.00) require a minimum dissolved oxygen level to protect biota of 6 mg/l (ppm) for SA waters, 5 mg/l (ppm) for SB waters, and 4 mg/l (ppm) for SC waters. Clearly the dissolved oxygen levels in both Massachusetts Bay and Nantucket Sound are above the minimum State Water Quality Standard.

Harmful Algae Blooms

Harmful algae blooms (HABs) are dense and sometimes regionally widespread concentrations of planktonic algae or dinoflagellates that can produce chemicals that are toxic to humans, birds, and aquatic biota. HABs originate when the required combination of physical and chemical ocean properties arise and can have profound financial and ecological implications. For example, researchers have determined that blooms of the dinoflagellate *Alexandrium fundyense* are related to concentrations of dissolved inorganic nitrogen, a nutrient required by photosynthesizing organisms, and silicate, a compound needed to build the exoskeletons of diatoms which may compete with *A. fundyense* (Townsend *et al.* 2005). The persistence of blooms and whether they move onshore may also depend upon physical factors such as wind velocities and water temperature. Recent work in Europe also suggests that dinoflagellate blooms can be controlled by cyclical host-specific parasitoid infections (Chambouvet *et al.* 2008).

Between April and July of 2007, more than 600,000 acres of shellfish areas on the North and South Shores, Cape Cod, and Boston Harbor, as well as offshore surf clam beds, were closed to shellfish harvesting due to an extensive *Alexandrium* bloom that spread from Maine to Massachusetts. The economic impact of these closures was projected to be $1.5-7.0 million. Other species that may form toxic blooms include *Alexandrium tamarense*, *Phaeocystic pouchetti*, and species within the genus *Microcystis*. Given their widespread spatial extent and the magnitude of their ecological and economic impacts, continued research toward identifying, predicting, and avoiding toxic blooms in the ocean management planning area will be necessary.

Nutrients

Concentrations of nutrients such as ammonium and nitrate, forms of nitrogen most readily used by phytoplankton, are monitored by MWRA in the area of Massachusetts Bay north of Cape Cod. Concentrations of ammonium in the nearfield, adjacent to the MWRA outfall, typically range from less than 1 μM to greater than 3 μM (0.02-0.06 ppm). A fifteen year data set indicates an increase in the annual average ammonium concentration from about 1 μM to 2 μM (0.02-0.04 ppm) immediately after the MWRA offshore outfall came online in September 2001, but that levels decreased back to 1 μM by 2005 and remained low in 2006. Concentrations of ammonium in Cape Cod Bay over the same time period remained fairly steady at 1 μM or less than 1 μM (Werme *et al.* 2008). Concentrations of nitrate, however, show large changes in concentration through a season. In Massachusetts Bay in 2006, nitrate levels were roughly 11.5 μM (0.71 ppm) in February, decreased to less than 2 μM (0.12 ppm) from April to July, and then increased through the remainder of the year. This seasonal pattern was consistent with long-term data. The 15-year data series also suggests that there was an increase in nitrate concentration in the 1990s in Massachusetts and Cape Cod Bays, but that concentrations have leveled off in the last five years (Werme *et al.* 2008). In Nantucket Sound, the average ammonium concentration over the summers of 2006 and 2007 was 0.011 mg/l (ppm) and the average nitrate+nitrite concentration was 0.001 mg/l (ppm). Average total nitrogen over this same time period was 0.290 mg/l (ppm) at the surface and 0.295 mg/l (ppm) at the bottom (Nantucket Soundkeeper 2008).

pH

pH is not routinely monitored by regional monitoring programs such as the MWRA, GoMOOS, or the National Data Buoy Center. However, it may be prudent to begin annual surveys of pH, as it has been predicted that ocean pH will increase with increasing global ocean temperatures and atmospheric CO^2 concentrations (IOC of UNESCO 2005). Ocean pH is important to organisms with calcium carbonate shells (*e.g*, bivalves and gastropods) because higher pH values are indicative of greater ocean acidity, which affects the formation and durability of carbonate shells.

Salinity

In general, salinity is lower near freshwater sources such as rivers, than offshore (except for the large freshwater discharge in Massachusetts Bay associated with the MWRA wastewater outfall). During the spring runoff and large storms, the freshwater input from the Merrimack River can noticeably change the surface salinity of Massachusetts Bay (*e.g.*, see Fig 3-7 in Werme *et al.* 2008). Salinity data from the Massachusetts A buoy collected between 2001 and 2008 (GoMOOS 2008) document an average surface salinity of 31.2 practical salinity units (psu) (range 20.7-33.2 psu) while that at the 50 m depth (164 ft) was 32.4 psu (range 29.7-33.4 psu). Salinity data collected by volunteers in Nantucket Sound over the summers of 2006 and 2007 (Nantucket Soundkeeper 2008) document a much more consistent average salinity of 31.6 psu (range 31.2-31.7 psu). There was no difference between the average salinity at the surface of Nantucket Sound (-0.3 m to -0.6 m; -1 ft to -2 ft) and the average salinity at the bottom (-6.6 m to -16.4 m; -22 ft to -54 ft).

Secchi Disk Depth

Sunlight availability is a major driver of primary productivity in marine ecosystems. One way to measure light penetration through the water column is to measure the maximum depth of visibility of a Secchi disk. Secchi disk depth gives a relative measure of the amount of particles (*e.g.*, suspended solids and plankton) in the water column. Low Secchi disk depths are associated with poor water quality because they indicate that relatively less light is available for photsynthesizers below the turbid water or because they indicate high densities of phytoplankton that may exude toxic substances or lead to low dissolved oxygen levels symptomatic of eutrophication. Mean Secchi disk depth in Massachusetts Bay from 2001 to 2005 as measured by MWRA was 7.3 m (24 ft). Values ranged from a mean of 2.9 m (9.5 ft) +/- 0.7 SD at the mouth of the Inner Harbor to a mean of 9.3 m (31 ft) +/0 2.9 SD at the monitoring site north of Provincetown. Cape Cod Bay had a mean Secchi disk depth of 7.7 m (25 ft) +/- 2.2 SD (MWRA, unpublished data). Mean Secchi depth in planning area waters off of Salem Sound in 1997 (Chase *et al.* 2002) was 3.8-4.7 m (12.5-15 ft). A survey of water quality in Buzzards Bay from 1987-1990 (Turner and Borkman 1993) reported that Secchi disk depths ranged from 0.75-9.0 m (2.5-30 ft) with a mean of 3.7 m (12 ft). Turner and Borkman (1993) also found that since most of Buzzards Bay is < 10m (32.8 ft) deep, the majority of the bay's waters are in the euphotic zone most of the time (*i.e.*, in the area with > 1% of surface light level). Mean Secchi depth in Nantucket Sound in 2007 was 4.0 m (13 ft) +/- 0.7 SD with values ranging from 2.9 m (9.5 ft) in Vineyard Sound to 4.8 m (16 ft) in the center of Nantucket Sound (Nantucket Soundkeeper 2008).

Sound

While not typically thought of as a water quality parameter, the amount of sound in the water column is an important feature that includes communication among marine mammals and fish as well as the more well-understood noise associated with human activities (*e.g.*, military operations, blasting, propeller use, drilling, *etc.*). Currently there is no systematic monitoring of sound in the planning area, except for the acoustic detection array managed by Cornell University in the area of the liquid natural gas deepwater ports off of Cape Ann and their approaches. The purpose of the array is to detect and locate marine mammal vocalizations in order to help prevent vessel strikes.

Total Suspended Solids

Total suspended solids (TSS), petroleum products, and dissolved metals are not systematically monitored for in the planning area, though they are pollutants that could affect the quality of marine habitats. Understanding their distribution and concentration may become important if extraction activities occur in the planning area at some point in the future. These constituents are modeled and monitored for in the vicinity of dredging projects on a site-specific basis (*e.g.*, when building pipelines or cables) and are monitored for through the NPDES program in industrial and municipal discharges that are in and outside of the planning area. The Massachusetts Water Quality Standards at 314 CMR 4.00 prohibit TSS discharges in concentrations greater than 100 mg/l (ppm), oil and grease above 15 mg/l (ppm), and dissolved metals in toxic concentrations. The amount of allowable metals and petroleum constituents in discharges is dependent upon criteria established by the U.S. Environmental Protection Agency to protect aquatic life (EPA 2008) and the available dilution in a waterbody.

BIOLOGICAL FEATURES

An important feature of the ocean's water column is that it is habitat for many species of fish, crustaceans, mollusks, marine mammals, reptiles, birds, and numerous other organisms. While some of these species are actively mobile through the water column (*e.g.*, nekton, mammals, reptiles, birds) the movement of others (*e.g.*, plankton) is completely dependent upon physical water characteristics such as currents and stratification. The mobility of water column organisms and their ability to avoid man-made disturbances (*e.g.*, blasting, dredging plumes) or infrastructure (*e.g.*, intakes, vessels, monopiles, mooring lines) is an important consideration for all aspects of ocean planning. Likewise, the fact that the water column is the location for breeding, foraging, migration, and all aspects of life history for many organisms speaks to its inherent importance as a near-shore habitat (described further in Chapter 4).

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FIGURES

Figure 2.1 Currents in the Gulf of Maine (from Pettigrew *et al.* 2005).

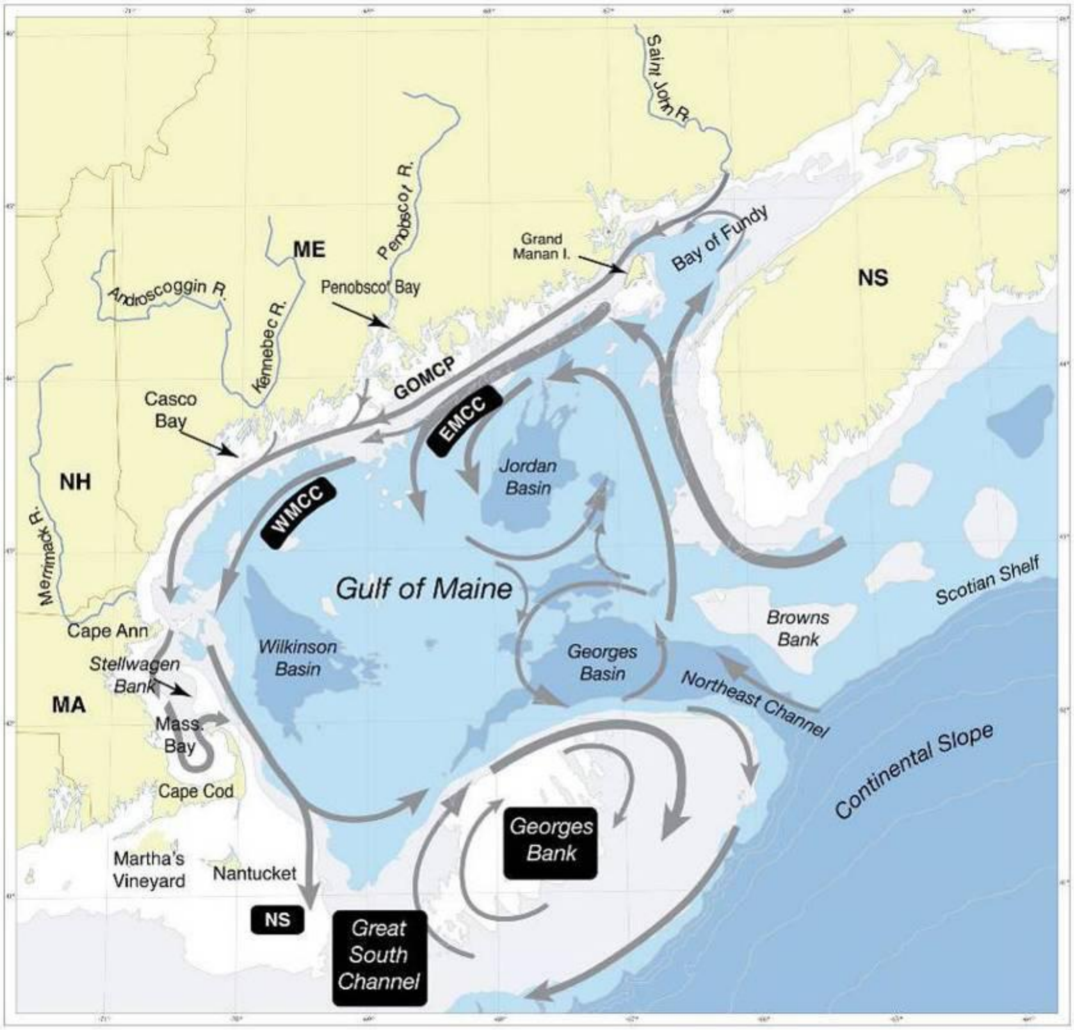

Figure 2.2 Waters South of Cape Cod.