OCEANOGRAPHY, WEATHER PATTERNS AND CLIMATE CHANGE

OCEANOGRAPHY

The oceanography of Massachusetts is influenced by physical, chemical and biological processes that act on regional and local scales. The North Atlantic Oscillation, for example, is a large global climatic pattern that influences the oceanography of the North Atlantic Ocean (including Massachusetts), and individual rivers entering Massachusetts coastal waters affect oceanographic conditions, such as current, salinity and temperature. These small and large features interact to influence the oceanography and ecological function of Massachusetts.

Massachusetts is located between two large marine systems, the Gulf of Maine (part of the Acadian province) and southern New England (part of the Virginian province). Forty-one percent of the Massachusetts coastline is bordered by the Gulf of Maine. The Gulf of Maine is a semi-enclosed sea, with Georges Bank and Browns Bank forming a barrier to the south and east, and the New Hampshire, Maine, New Brunswick, and Nova Scotia coastlines containing the Gulf.

Situated in the western Gulf of Maine, the Massachusetts and Cape Cod Bays are partially isolated from the rest of the Gulf by Stellwagen Bank. On either side of the Bank are two channels: one between Cape Ann (Gloucester) and Stellwagen Bank; and, the other, between Race Point (Provincetown) and the Bank. Stellwagen Basin is the deepest portion of Massachusetts Bay, with a depth of 80 m; the depths of the channels are 60 m and 50 m, respectively.

There is a persistent counterclockwise current in Massachusetts Bay that also exists in the Gulf of Maine; however, seasonal variation in direction and intensity of the major currents and many smaller currents exist. The major current enters south of Cape Ann, flows south through most of the Bay, and exits north of Race Point. The currents in Cape Cod Bay are fairly weak except during a run-off period when the counterclockwise circulation existing in Massachusetts Bay flows to Cape Cod Bay.

Southern Massachusetts is found in southern New England, which is considered the northern edge of the Mid-Atlantic Bight. Nantucket Shoals, a submerged sand and gravel shallow ridge, extends southeastward from Nantucket Island. Buzzards Bay is a relatively shallow estuary with depths to slightly over 20m. There are two major currents in the Bay; the first running parallel to Naushon Island and terminating near Woods Hole (average current speed=0.6 to 0.8 knots); and the second runs along the northwest shore of the Bay (average current=0.6 knots).

The Gulf Stream brings warm water from the south, from the coast of Florida, moving east off the North Carolina coast and then northeast across the Atlantic Ocean. At the Grand Banks, the Gulf Stream changes from a single front to two branching fronts: one branch is called the North Atlantic Current and curves north along the continental slope, eventually turning east; the second branch is called the Azores Current and flows southeastward towards the Mid-Atlantic Ridge.

Coastal Landforms

The Massachusetts coast is lined with a diversity of landforms, including salt marshes, barrier beaches, estuaries, salt ponds/coastal embayments, open coastal waters, and rocky shores. It is this diversity that provides varying tidal and current characteristics; and this diversity is an illustration of the geology throughout Massachusetts, with rocky outcrops more prevalent north of Cape Cod and a higher proportion of sandy environment in southern Massachusetts (please refer to the Estuarine and Marine Habitat section for further information on coastal habitats and land forms).

Major Currents and Tides

Tide is the vertical rise and fall of water accompanied by the horizontal movement of the water, known as a tidal current. The moon and sun generate tidal forces. However, weather, seismic events, or other natural forces also influence tides and river flows; floods or other non-tidal currents also affect tidal currents. Current is affected by differences in bathymetry or the depth of the ocean. Currents and tides are also affected by wind and atmospheric pressure (NIMA 1995). The movement of water by tides, currents and waves influence environmental processes from nearshore to offshore waters, such as erosion and deposition of sediments.

Across the Massachusetts coast, the mean tide range (measurement of the rise and fall of the water between high and low tides) ranges from one to thirteen feet. In extreme weather events, for instance the Blizzard of 1978, the tide was five feet above normal high water, which resulted in the highest tide recorded at Boston Harbor's NOAA Station. The lowest tide recorded was approximately four feet below normal low water in March 1940.

There are many local currents along the Massachusetts coast. For example, White (2004) noted one of the strongest currents on the Massachusetts coast is at the Woods Hole Cut that connects Buzzards Bay with Vineyard Sound and averages a maximum velocity of 4.5 knots. Average current velocities through the man-made Cape Cod Canal approach 4.5 knots, the result of significant tidal height differences between Cape Cod Bay and Buzzards Bay. The location or characteristics of small, localized currents are generally not identified or described.

Riverine Inputs

Riverine systems are comprised of streams and rivers, connecting upland streams and wetlands with the ocean. Rivers carry freshwater, nutrients, and pollutants throughout the watershed. Riverine systems, estuaries, and other systems that include freshwater marshes, swamps, bogs, lakes, etc. form the Commonwealth's watersheds. Eventually, all Massachusetts watersheds drain into a coastal water body; these include the

Massachusetts/Cape Cod Bays complex, the Vineyard Sound/Nantucket Sound/Atlantic Ocean area, Buzzards Bay, Mount Hope Bay, Long Island Sounds or New York Harbor (MCZM/MME 1992).

The United States Geological Survey (USGS) collects data on the variations of stream flow across Massachusetts. Flanagan (1999) states the largest rivers carry the greatest amount of stream flow; the Merrimack River is the largest river in Massachusetts. Stream flow is typically highest during spring runoff and snowmelt; however, fall rains may also be substantial.

There are no extraordinarily large rivers entering Massachusetts Bay, south of Cape Ann; the largest entering southern waters of the Bay is the Charles River at an average annual discharge rate of 10 $m^3 s^{-1}$ and the Merrimack River has a substantial average annual discharge, 320 $m^3 s^{-1}$, and enters northern Massachusetts Bay. There are several freshwater riverine influences north of the Bays into the Gulf of Maine; the Penobscot River has an average annual discharge of 475 $m^3 s^{-1}$ and the Androscoggin and Kennebec Rivers have an average annual discharge rate of 320 $m^3 s^{-1}$. These riverine discharges influence water conditions in Massachusetts.

Aside from the Charles River, the MWRA discharges into the Massachusetts Bays via Boston Harbor and contribute a substantial volume of freshwater to the Bay. Together, the Charles River and MWRA discharges account for only a few percent of the discharge of the Gulf of Maine Rivers. Geyer et al. (1992) states that the percentage of other rivers discharged into the Bays appears highly variable and has not been well quantified. These rivers may include the Ipswich, Neponset, and Acushnet Rivers, among others.

WEATHER CONDITIONS

Continental air masses from the south and west and warm air from the Gulf of Mexico influence the Massachusetts climate. Weather conditions in the North Atlantic region are controlled by the Bermuda high pressure system. This condition results in frequent showers, thunderstorms, high humidity, and low wind speeds in the spring and summer and, in the winter, can result in frequent and abrupt day-to-day variations in pressure, wind, and weather when combined with faster moving and more intense winter pressure systems (Field 1980).

Generally, winds vary over seasons in Massachusetts. Summer winds typically are weak from the southwest or southeast and bring warm, moist air that can contribute to fog formation; winds from the north or northwest are typical for autumn and winter (GoMOOS 2003). Spring and summer southwesterlies may drive hurricanes northward from cross Atlantic or Caribbean tracks and have the potential to harm the Commonwealth's south-facing shores (e.g. Buzzards Bay and the south coast of Cape Cod). The storms of autumn or winter, "nor'easters," also have particularly strong winds and may drive winter storms into northeastern-facing shores (e.g. Massachusetts Bay and the outer Cape) (MCZM/MME 1992). Storm surge is another hazard characterized by elevated sea level along a coast caused by storms. Coastline shape, nearshore depth and wind strength and direction all determine the severity of storm surges (GoMOOS 2003).

Recently, Wind Energy Resource Maps were developed for New England, in a collaborative effort by the Connecticut Clean Energy Trust, Northeast Utilities and the Massachusetts Technology Collaborative. This report and accompanying maps may be found online at http://www.mtpc.org. Wind conditions were projected using the MesoMap system: A Mesoscale Atmospheric Simulation System (MASS) that is a numerical weather model using online, global, geophysical, and meteorological databases. This system creates a wind resource map by simulating weather conditions over 366 days selected from a 15-year period.

According to the report and maps, a concentration of the wind resources of Massachusetts are in the hills of western Massachusetts, coastal areas, and offshore. Offshore winds are predicted to be very strong with mean speeds of at least 8.5m/s at distances greater than 10-20 km from the shore at 65 m above the effective ground level (2/3 the height of tree tops or 10 m). On land the mean speed at the same height typically range from 5.5 to 7 m/s. The main factor for this difference is “surface roughness”; forests exert friction on the atmosphere causing the speed near the surface to be reduced. However, taller hills and mountains in western Massachusetts have mean wind speeds at the highest points predicted to exceed 9m/s; these areas may have strong winds occurring aloft. Moderate ridges show predicted speeds of 6.5-8 m/s. Small peninsulas and exposed islands may also be locations for a productive wind resource, such as Cape Cod, Nantucket or Martha’s Vineyard.

CLIMATE CHANGE

Over the next century, climate change is projected to profoundly impact coastal and marine ecosystems, not just in Massachusetts but also, around the globe. Such trends as sea level, increased coastal flooding, inundation of wetlands, and changes in ocean and atmospheric circulation are predicted to occur.

These effects have been observed in many recent reports, including those recently issued by the Conference of New England Governors – Eastern Canadian Premiers in their Climate Change Action Plan (August 2001):

> Scientific evidence of the destabilizing human influence on global climatic systems is continuing to build, creating a growing momentum for a response. For example, the Intergovernmental Panel for Climate Change (IPCC), an international body of atmospheric scientists, in its *Third Assessment Report*, states that “There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.” …. The IPCC predicts that if no action is taken, average rates of warming by 2100 will “be greater than any seen in the last 10,000 years.” Such instability will increase the incidence and severity of extreme weather events such as storms, droughts, floods, and heat

> waves; cause sea levels to rise; shift and/or expand certain disease and pest vectors; and further stress already vulnerable species and ecosystems.
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> In the *Canada Country Study, Atlantic Region Report*, for example, scientists predicted that sea level rise is the impact with the highest degree of certainty associated with it and will lead to predictable and dramatic impacts. Many of these impacts would be common to the Eastern Canadian provinces and to New England states. The warming would stress our common natural resources—especially in the areas of agriculture, fisheries and forestry. Another recent analysis of regional impacts of future climate change in the United States, concluded that key issues for New England (and we can assume for the Eastern Canadian provinces as well) were likely to include an increase in weather extremes; stresses on estuaries, bays, and wetlands; changes in precipitation rates impacting water supply and food production; multiple stresses on urban areas; and recreation shifts. …. Rising sea level and elevated storm surge levels—with associated problems of coastal erosion and saltwater inundation—would likely have severe impacts on our harbors, islands, and for the many communities located near the region's shoreline.

Additionally, as cited by the recent Pew Ocean Commission, among the effects of climate change on the oceans are: changes in precipitation, wind patterns, and the frequency and intensity of storms; warming temperatures will influence reproduction, growth, and metabolism of many species in stressful or beneficial ways, depending on the species; impacts (potentially beneficial as well as harmful) on aquaculture; species migration, which could change the mix of species in particular regions; sea-level rise could threaten the survival of marshes; changes in wind patterns could affect coastal and estuarine circulation patterns and upwelling and downwelling of water in marine systems; changes in the frequency and intensity of storms could increase flooding and threaten coastal aquaculture and fishing industry facilities; natural climate variability, such as El Niño events, results in changes in open-ocean productivity, shifts in the distribution of organisms, and modifications in food webs, foreshadowing what would happen if climate change accelerated; changes in temperature or salinity of North Atlantic water in the Arctic, which may slow or shut down the slow-moving thermohaline circulation that delivers cold, dense, oxygenated water to the deep sea; and climate-induced changes in ocean chemistry could diminish the abundance of microscopic open-ocean plants and animals. (Pew Commission, "America's Living Oceans: Charting a Course for Sea Change," May 2003, Chapter 7.)

Clearly, as a state with significant ocean and coastal resources, Massachusetts has had to and will need to continue to adapt to effects such as these. For example, an examination of the Massachusetts coast on the geologic timescale shows that the climate and sea level have been quite variable. The climate of the earth has been warmer, glaciers melted and sea levels were higher; up to 100 meters higher between the Nebraskan and Kansan glacial periods. The climate of the earth was also cooler and with the capture of the water in glaciers the sea levels lower, up to 100 meters lower at the height of the last glacier period called the Late Wisconsin Period about 17,000 years ago. Since that time, glaciers melted and sea level rose at a rate of about 40 inches per century (0.033 ft/yr). The rate of sea level rise is not constant; geologists estimate the peak rate was approximately 30 feet per century (0.300 ft/yr), occurring about 6,000 years ago when all low-lying coastal areas were flooded. In the last 6,000 years, sea level change was not as dramatic, with sea level no more than 10 to 12 feet higher or lower than it is today. The current amplitude of the sea level oscillation also appears dampened in the past 6,000 years, going from 20-foot oscillations to five-foot oscillations (Fairbridge 1960).

Climate change and sea level change are related, and anthropogenic impacts can be added to the many natural variables that affect climate and sea level. The Intergovernmental Panel on Climate Change (IPCC) noted that the average surface temperature of the earth has increased since 1861, and has increased over the last 100 years by about 0.6°C (1°F). The 1990s was the warmest decade since instrumental recording began in 1861, with 1998 being the warmest year. Global sea level has risen 10-20 cm (4-8 inches) over the past century; and there was an increase in the heat content of the upper 300 m (985 ft) of the ocean by about 0.04°C (0.07°F) since the 1950s (IPCC 2001).

This warming has been attributed to increases in greenhouse gases, particularly carbon dioxide, methane, water vapor, chlorofluorocarbons and nitrous oxide. The warming rate of the earth depends on the ability of the atmosphere to achieve equilibrium, the rate of increase in atmospheric CO_2 and other greenhouse gases and the ocean's capacity to absorb heat that would warm the earth's atmosphere.

Global warming raises sea level in two ways. First by thermal expansion, warming will decrease the density of ocean water thus increasing its volume (i.e., the same amount of water will take up more space when heated). The rate at which more space is taken depends on how much heat is absorbed by oceans. The second way sea levels rise from global warming is by the transfer of snow and ice from land to the sea. Glaciers contain large volumes of water trapped as ice and melt, resulting in water entering the ocean and raising sea level (if not displaced by increased snowfall on land or glacier formation). The melting of the glaciers may be a phenomenon in which a threshold exists. Once the threshold is exceeded, glaciers may melt at an exponential rate, regardless of climate change, thus increasing water run off to oceans and sea level rise (self-reinforcing process / cascading effect).

Measuring Sea Level

Tide gauges are instruments usually located on piers that continuously measure sea level height. The gauge's height is precisely leveled at a known benchmark height (marked in bedrock). Hicks et. al. (1983) examined data from 44 (of the 67) permanent tide gauge stations operated by the National Ocean Service which were operational prior to 1940 and had few breaks in their measurement series. Two of these stations are in Massachusetts – Boston and Woods Hole.

The Boston station is located behind the Coast Guard Offices on Atlantic Avenue on the old Northern Avenue Bridge (latitude 42° 21.3' N, longitude 71° 03.0W). The first full year of tidal information was 1922 and it has been providing data since that time.

The Woods Hole gauge is located at the Woods Hole Oceanographic Institution (latitude 41° 31.5’ N longitude 70° 40.4W). The first full year of tidal information was 1933, and data from 1965 and 1967-1969 is not available.

Hicks et. al. (1983), among other analyses, examined the yearly mean sea level that is the arithmetic mean of a calendar year of hourly heights through 1980. Boston and Woods Hole both showed increasing trends in sea level height, with increase in Boston at 2.3 mm/year (0.008 ft/year) and increases in Woods Hole at 2.7 mm/year (0.009 ft./year).

Sea level data is available through 1993 from the National Ocean Service’s web site (http://www.co-ops.nos.noaa.gov/seatrnds.html). Boston and Woods Hole continue to show increasing trends of 2.64 mm/yr (0.0084 ft./yr) and 2.48 mm/yr (0.0081 ft./yr), respectively. Data only using the series from 1950-1993, a common series for all stations, show increasing trends of 1.74 mm/yr (0.0057 ft./yr) for Boston and 2.05 mm/yr (0.0067 ft./yr) for Woods Hole.

All areas in the United States, except the northern west coast (northern California, Oregon and Washington), show increasing sea level trends. Sea level is increasing from 1.0 - 2.6 mm/year (0.003 ft.- 0.009 ft.). The northern west coast has a negative trend of -0.4 mm/yr (-0.001 ft./yr). The United States overall has an increasing trend of 1.3 mm/yr (0.004 ft./yr.).

Another method to measure sea level is with a satellite altimeter, which measures the sea level from a precise orbit around earth. These measurements of global sea level change are very exact over shorter periods of time. Since August of 1992, the TOPEX/POSEIDON satellite mission measured sea level on a global basis every 10 days with unprecedented accuracy and precision; these data can be used to further evaluate changes in sea level.

SUMMARY

Oceanographic conditions in Massachusetts are fairly unique. Massachusetts is part of the Gulf of Maine and southern New England. The oceanography of our region is not fully described, but ongoing monitoring efforts (e.g., Gulf of Maine Ocean Observing System; GoMOOS) are improving our understanding of the variability of oceanographic conditions (e.g., water movements). Temporal and spatial variance in oceanographic conditions are important to identify because this variability affects natural resources and weather. Climate change, for example, can have substantial impacts on coastal and ocean resources. Climate change and sea level rise will alter hydro-cycles, and the results could be more intense storms and more extreme floods and droughts. Sea level rise will also cause beach erosion and beach narrowing, dune and bank erosion, wetland loss, alteration of species assemblages, infrastructure usability loss and the possibility of complete loss, low lying area flooding, island re-sizing, and ground water implications. A comprehensive ocean resources monitoring and research plan should encompass a range of oceanographic measurements and indicators of climate change and sea level rise.

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