8. CLIMATE CHANGE

Over the next century, climate change is projected to profoundly impact coastal and marine ecosystems around the globe. A variety of impacts related to warming are already being seen in Massachusetts. Such trends as increasing ocean and air temperatures, sea level rise, increased coastal flooding, oceanic acidification, and changes in ocean and atmospheric circulation including increasing storm frequency and intensity are predicted to further impact Massachusetts. There is abundant literature regarding temperature change and sea level rise. In contrast, less is known about climate change impacts on oceanic ecosystems and storms.

We discussed both "Environmental Change" and "Climate Change" as the chapter title. Environmental Change suggests something beyond Climate Change so I am in favor of Climate Change. Also, the Act specifically talks about Climate Change.

TEMPERATURE CHANGE

Major contributor: Bob Glenn

The average surface temperature of the earth has increased by about 0.74°C (1.3°F) between 1906 and 2005. The warmest years since instrumental recording began in 1861 are 1998 and 2005, and 11 of the 12 warmest years have occurred in the last 12 years (1995 to 2006) (IPCC 2007). In the Northern Hemisphere, seasonal changes are apparent. The ice season is shorter and the frost-free period is longer. In other words, spring comes earlier. Within Massachusetts, the rate of annual trends in atmospheric temperature change show a 0.14-0.22°C (0.25-0.40°F) increase per decade over the past 30 years (NWS 2008).

This warming of the atmosphere and oceans is a function of a shifting balance between incoming short-wave radiation, outgoing long-wave radiation, and the reflection of solar radiation (albedo). Increases in greenhouse gases (*e.g.*, carbon dioxide, methane, water vapor, chlorofluorocarbons, and nitrous oxide) reduce the outgoing long-wave radiation. Other processes that can cause both climatological earth cooling (large volcanic eruptions) and warming (sun spot variation) occur over different time periods. Currently, the balance has tipped toward warming, and there is consensus that globally and locally ocean waters have been warming over the past several decades

There are several datasets in Massachusetts waters that show evidence of warming in or near the planning area.

1. The WHOI dock temperature monitoring has been measuring sea surface temperature (SST) in Great Harbor, Falmouth, MA since 1886 with few gaps. The record shows significant warming from 1970–2002 at a rate of 0.04°C yr^{-1} (0.07°F yr^{-1}). This record does not show an "earlier spring." The dates the water reach 10°C (50°F) and 20°C (68°F) have not changed significantly, nor have the number of winter days below 1°C (34°F) or above 5°C (41°F) (Nixon *et al.* 2003).

2. NOAA monitors SST at Woods Hole (since 1995), Fall River (since 1900), Nantucket (since 1998), and Boston Harbor (since 1922 at one station, since 1997 at another station). These records are available for further analysis.

3. *MarineFisheries* has long-term temperature monitoring stations at locations throughout the state (Figure 8.1). Since 1988, SST data is available through the shellfish classification database which contains sites primarily in embayments. The Fisheries Resource Assessment program measures the bottom temperature at all tow locations during its assessment trawls in May and September (since 1978). There are also several continuous bottom temperature datasets overseen by the Coastal Lobster Investigation program: Cleveland Ledge (since 1990, in 11 m (35 ft) of water), Buzzards Bay (since 1989, in 21 m (70 ft) of water), sites in Cape Cod Bay at 18 m (60 ft), 27 m (90 ft), and 37 m (120 ft) water depth, and temperature data on lobster traps (the last few summers). Some datasets have received preliminary analysis, and show a general warming trend.

4. Massachusetts Water Resources Authority (MWRA) conducts basic water quality monitoring throughout Boston Harbor and Massachusetts Bay. This data is available for further analysis.

Warming can have major ecosystem effects including altering the distribution and abundance of species. Within Massachusetts, such population-level effects are being seen in species at the southern edge of their range like cod and smelt. Similarly, expanded ranges of more southerly species such as summer flounder and lady crabs are being seen. Based on preliminary analysis, it appears that a significant variable to investigate with temperature datasets is the number of days above 20°C (68°F), and possibly the degree of stratification.

CHANGES IN PRECIPITATION

This section is not in the current outline, and needs to be "voted in" by the council.

A potential consequence of warming is changing patterns of precipitation. The current evidence suggests that New England will see little change in current precipitation patterns (IPCC 2007). In contrast, the long-term trend data illustrates an annual average increase of 1.5 inches per decade over the past 30 years (NWS 2008). There are potential impacts on the ecosystem governed by both the quantity of freshwater entering the planning area as well as the seasonality and intensity of rainfall events. The importance of water for human health, agriculture, and ecosystem functioning is significant enough that a higher resolution examination of these trends is warranted.

SEA LEVEL RISE

Climate change and sea level change are related. Increasing global temperature raises sea level in two ways: first, through thermal expansion, in which warming increases water volume and second, through melting and flow of land-based snow and glacial ice into the sea. The melting of 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). [This came from the Task Force reports; what is source?]

The rates of global warming-induced sea level rise can be either exaggerated or mitigated in local regions depending on the nature of the vertical movement of underlying geology (isostacy). Southern New England is subsiding in response to isostatic uplift in Canada from deglaciation over the past 10,000 years. The rate of subsidence could be between 1.0-6.0 mm/yr (0.04-0.24 in/yr) as measured by the Global Positioning System (Milne 2005). Although sea level predictions typically take this into account, it is worth pointing out that there could potentially be significant error in local sea level rise predictions due to the imprecision of isostacy modeling along the U.S. East Coast (Davis *et al.* 2008).

An examination of the Massachusetts coastal sea level has been quite variable over geologic timescales. Estimates of the higher rates of change range from 9.1 mm/yr (0.36 in/yr) to 91 mm/yr (3.6 in/yr), occurring about 6,000 years ago when all low-lying coastal areas were flooded. In the last 6,000 years, however, sea level change was not as dramatic, with sea level no more than 3-3.5 m (10-12 ft) higher or lower than it is today (Comm. Mass. 2004). Most areas in the United States show increasing sea level trends ranging from 1.0-2.6 mm/yr (0.04-0.1 in/yr) with the exception of parts of the northwestern United States (NOS 2008).

Sea levels are continuously measured with tide gauges that are usually attached to piers. The elevation of a particular gauge's height is precisely leveled relative to a known benchmark height (marked in bedrock). Sea level trends in Massachusetts are computed utilizing gauges at Boston, Woods Hole, and Nantucket. The Boston station has been providing tidal sea level data since 1921. The Woods Hole gauge was placed in 1932, but data from 1965 and 1967-1969 is not available (Hicks *et al.* 1983). The Nantucket station has tidal sea level data continuously from 1965. The trend information was first computed by Hicks *et al.* (1983) but is now easily available through NOAA's Tides and Currents website which provides graphs of sea level trends for all tide gauges in the United States. The trends for Massachusetts show an average increase of 2.73 mm/yr (0.11 in/yr). Details for each tide gauge based on the long-term linear trend as described by the National Ocean Service (2008) are provided in Table 8.1.

Table 8.1. Tide gauge sea level trends in Massachusetts from first year to 2006.

Gauge/Station Name	First year	Number of years	Trend in mean sea level (mm/yr; in/yr)	95% confidence interval (mm/yr only)
Boston	1921	86	2.63; 0.1	0.18
Woods Hole	1932	75	2.61; 0.1	0.20
Nantucket Island	1965	42	2.95; 0.12	0.46

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 have considerably better accuracy, precision, and spatial resolution. Since August of 1992, the TOPEX/POSEIDON and Jason-1 satellite missions measured sea level on a global basis every 10 days. Estimates from studies examining satellite altimetry trends in sea level range from about 3.0-4.5 mm/yr (0.12-0.18 in/yr) in contrast to the 20th century gauge rate of 2 mm/yr (0.08 in/yr) (Douglas 1991, Miller and Scharroo 2004, Nerem 2005, Mangiarotti 2007).

The discrepancy between the gauge and satellite rates is currently thought to be a real indication of the increasing rate of sea level change in the last decade or so (Nerem 2005). Therefore, the gauge rates might be significantly underestimating the rate of sea level change. A higher resolution examination of the rate and potential impacts of sea level rise in Massachusetts is possible with further analysis of satellite data.

The first effects of sea level rise are already being felt in Massachusetts: inundation of low-lying areas, increased area of inundation during storms, and increased shoreline erosion.

INCREASING FREQUENCY AND INTENSITY OF STORMS

Reviewed by Kerry Emanuel, MIT

The increasing frequency and intensity of storms (*i.e.*, increased storminess) is one of the hypothetical outcomes of increasing sea surface and atmospheric temperatures. There is debate surrounding the probability and spatial extent of this type of impact; in general the empirical evidence based on the historical record suggests sea surface warming does not correlate with increased frequency of storms (number of storms per year), but does correlate to increased storm power (Emanuel 2005). While the extent of future increases in storm power is still very uncertain (Emanuel *et al.* 2008), Wake *et al.* (2006) summarized climate trends in the northeastern U.S. and found that extreme precipitation events (> 50 mm or 2 in of rain) increased in Massachusetts from 1950-2002. A further complication regarding the impacts of increased storminess is the added effect of sea level rise and the compounding effect it can have on coastal storm damage. As a result, coastal impacts can be out of proportion to the size of a given storm due to the impacts of hard-to-predict storm surges (Resio and Westerink 2008).

The issue of storminess is very important for three reasons: 1) both hurricanes and nor'easters play a key role in the ecosystem and the safety of coastal populations, 2) current demographic trends and government policies suggest continued population increases along the coast, and 3) the performance capabilities of offshore structures are defined using storminess (*e.g.*, a North Sea oil rig). The increase in coastal population will result in increased user conflicts in the planning area and increased interest in offshore extraction of mineral resources for shoreline protection and recreational use (as is seen in other densely population coastlines including New Jersey, Florida, Belgium, and Denmark). Increased storminess should also be considered when determining how to monitor ecosystem change and establishing performance standards required of offshore construction proponents.

OCEAN ACIDIFICATION

Dissolving CO_2 in seawater increases the hydrogen ion (H^+) concentration in the ocean, and thus decreases ocean pH. A decrease in pH is known as acidification and below a pH of 7, conditions are described as acidic. pH is measured on a negative logarithmic scale, so a 0.1 point decrease means H^+ has increased by about 30%. Ocean pH has decreased by 0.1 units since 1750 and there is consensus that ocean acidification will continue (IPCC 2007). By 2050, the surface ocean water pH is predicted to be between 0.3 and 0.7 units lower than pre-industrial levels due to the absorption of atmospheric CO_2 (Caldeira and Wickett 2003, Orr *et al.* 2005). The trend of pH measurements in Massachusetts (reference –MWRA data?). Streams in Massachusetts are showing improved water quality and increasing pH levels (Mattson *et al.* 1997).

There is concern within the scientific community that the resulting decrease in pH will have negative consequences for organisms with calcium carbonate in their exoskeltons, since pH values less than 7 can result in dissolution of calcium carbonate. Organisms that could be impacted in Massachusetts include lobsters, clams, and organisms at the base of the food chain such as coccolithophores and foraminifera. However, consensus regarding impacts related to ocean acidification is lacking since laboratory conditions suggest a strong influence of local conditions governing calcification (IPCC 2007). None-the-less, impacts of decreasing pH levels in the planning area are feasible and might be significant due to our reliance on seafood both recreationally and commercially.

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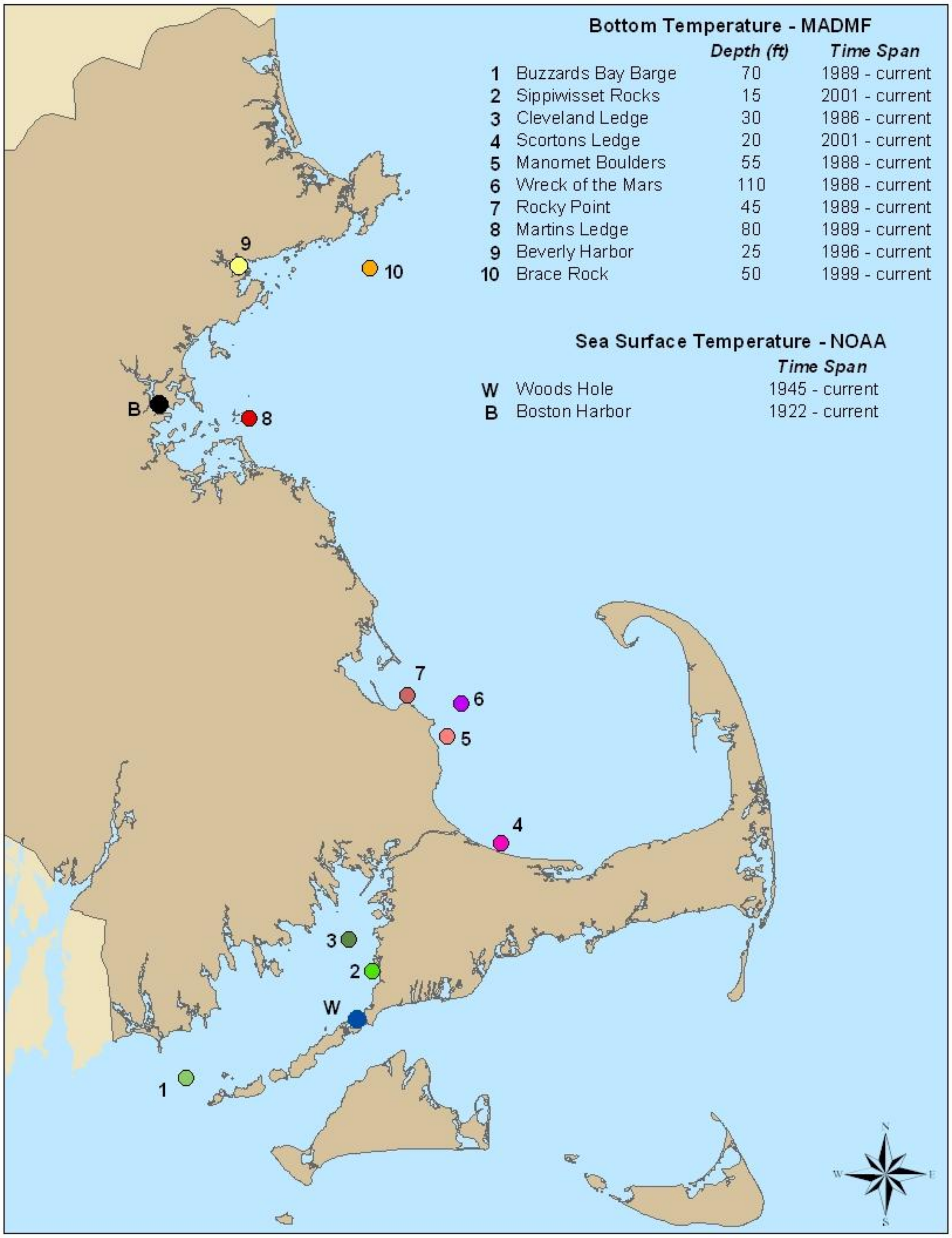
Figure 8.1. Location of temperature monitoring stations in Massachusetts. (Add MWRA and shellfish monitoring stations)



Bottom Temperature - MADMF

		Depth (ft)	*Time Span*
1	Buzzards Bay Barge	70	1989 - current
2	Sippiwisset Rocks	15	2001 - current
3	Cleveland Ledge	30	1986 - current
4	Scortons Ledge	20	2001 - current
5	Manomet Boulders	55	1988 - current
6	Wreck of the Mars	110	1988 - current
7	Rocky Point	45	1989 - current
8	Martins Ledge	80	1989 - current
9	Beverly Harbor	25	1996 - current
10	Brace Rock	50	1999 - current

Sea Surface Temperature - NOAA

		Time Span
W	Woods Hole	1945 - current
B	Boston Harbor	1922 - current