Potential impacts of climate change and variability on shellfish resources

An overview prepared by the

Working group on Climate Change impacts on shellfishing in Wellfleet Harbor

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Summary

A key finding of a recent assessment is that climate change will exacerbate heat waves, coastal flooding, and river flooding in the northeastern United States (Horton et al. 2014). Both air and water temperatures are expected to increase as a result of climate change. Across the continental US precipitation is falling in more intense events, which is consistent with predictions for the impacts of climate change. This trend is especially strong in the northeastern US. Some of these heavy precipitation events will be in the form of hurricanes and winter northeasters. Furthermore, the number and power of severe storms is predicted to increase in the future, even as the overall frequency of storms may decrease. Heavy precipitation events, particularly winter northeasters and hurricanes, are accompanied by storm surges, which can exacerbate near-shore flooding. Sea level rise will increase near-shore flooding as well. In addition, ocean chemistry is changing, and the main focus of attention has been ocean acidification, which occurs when increased CO_2 uptake reduces available carbonate ions.

Shellfish play a vital role in the ecology of Wellfleet Harbor and the economy of Wellfleet. Currently, Wellfleet produces about 23% of the shellfishing landings in the Commonwealth, worth approximately $4,500,000. Wellfleet ranks second to Duxbury in terms of commercial shellfish production. However, shellfish are particularly vulnerable to climate change and variability. The National Marine Fisheries Service ranks shellfish as among the most vulnerable of fish stocks in the northeastern US (Griffis 2015).

This report provides an overview of the climate-related threats to shellfish and commercial shellfishing in Wellfleet Harbor. In Wellfleet Harbor the main climate-related threats are: sea level rise, changes in intensity and frequency of heavy precipitation, rising water and air temperatures, and ocean acidification. Heavy precipitation events often occur in combination with storm surge and high winds, which can exacerbate impacts especially as sea levels rise.

The purpose of this report is to summarize the Working Group's discussions related to sea level rise, including potential impacts to shellfish and shellfishing in Wellfleet Harbor and adaptation strategies. Information about the Working Group, including its goals and members, can be found in Appendix A and at the project website: www.seri-us.org/content/fisheries-and-climate-Wellfleet. The Working Group used the Vulnerability, Consequences, and Adaptation Planning Scenarios (VCAPS) process to organize its discussions (Webler et al. 2014; an overview is provided in Appendix A).

Potential impacts to health of harbor, shellfish resources, and commercial shellfishing in Wellfleet Harbor from sea level rise.

- *Change the proportion of inter-tidal and sub-tidal habitat areas.*
- *Alter species' location and composition, including predators of shellfish as habitat type and availability shifts.*
- *Degrade water quality in Wellfleet Harbor.*
- *Change how shellfish can be grown and harvested.*
- *Disrupt access to grants and lead to inadequacy of infrastructure.*
- *Lead to resource use conflicts.*

Potential impacts to health of harbor, shellfish resources, and commercial shellfishing in Wellfleet Harbor from changes in intensity and frequency of heavy precipitation.

- *Increase diseases and pathogens affecting both oysters and quahogs.*

- *Degrade water quality in Wellfleet Harbor.*
- *Disrupt access to grants from coastal erosion caused by severe storms and storm surge (in combination with rising sea levels).*
- *Decrease economic revenue due to increased pathogens, shellfish diseases, mortality and morbidity of shellfish, and harmful algal blooms.*
- *Alter sediment transport, which can impact the health of shellfish and alter suitability of grants for aquaculture.*

Potential impacts to health of harbor, shellfish resources, and commercial shellfishing in Wellfleet Harbor from warming air and water temperatures.

- *Increase diseases and pathogens affecting both oysters and quahogs and selectively benefit predator species.*
- *Increase shellfish mortality due to summertime oxygen depletions.*
- *Increase exposure risks to those who work the shellfish beds.*
- *Decrease formation of ice and allow predators and pathogens to over-winter.*
- *Decrease economic revenue due to increased pathogens, shellfish diseases, and harmful algal blooms.*
- *Decrease economic revenue due to reduced reproductive rates.*
- *Decrease economic revenue due to incidents of human pathogens (e.g., Vibrio parahaemolyticus) or to the imposition of new rules to reduce risks of outbreaks.*

Potential impacts to health of harbor, shellfish resources, and commercial shellfishing in Wellfleet Harbor from ocean acidification.

- *Decrease growth rates and survival rates of shellfish.*
- *Decrease economic value of shellfish and decrease revenue of shellfisherers.*
- *Change how shellfish can be grown and harvested*.

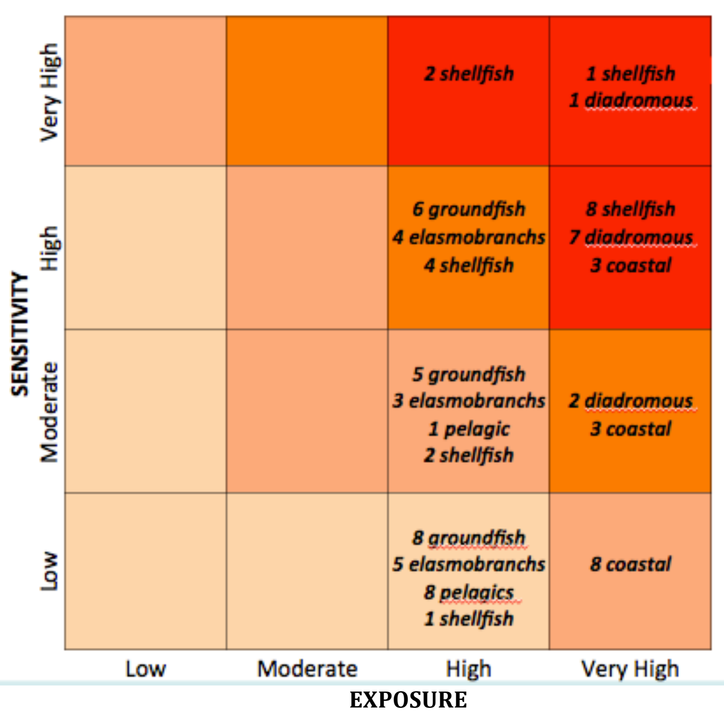
Introduction

A key finding of a recent assessment of the northeastern US is that "heat waves, coastal flooding, and river flooding will pose a growing challenge to the region's environmental, social, and economic systems" (Horton et al. 2014, pg. 372). They will pose a particularly significant challenge to the shellfish sector in New England. Climate change and variability will have significant impacts on shellfish resources over the long term, as well as the communities that rely on them (Burkett and Davidson 2012, Ekstrom et al. 2015, Horton et al. 2014, Titus et al. 2009). Rising sea levels will alter shorelines, coastal ecology, and access to grants. Changing air and water temperatures and precipitation patterns will alter sea water quality, habitat, and work routines, as well as the prevalence of shellfish and human pathogens. The frequency and intensity of harmful algae blooms are likely to increase. Changes in species composition are likely to result from a combination of multiple climate-related factors.

Shellfish are particularly vulnerable to climate change and variability. The National Marine Fisheries Service ranks shellfish as among the most vulnerable of fish stocks in the northeastern US (Griffis 2015). A preliminary assessment by the National Marine Fisheries Service concludes that exposure to climate change in Northeast U.S. is high to very high. The sensitivity of marine species to climate-related stressors varies, but as shown in Figure 1 one or both of exposure and sensitivity of shellfish to climate stressors in the northeastern US tend to be high.

In Wellfleet Harbor the main climate-related threats are: sea level rise, changes in intensity and frequency of heavy precipitation, rising water and air temperatures, and ocean acidification. Heavy precipitation events often occur in combination with storm surge and high winds, which can exacerbate impacts especially as sea levels rise. Shellfish play a vital role in the ecology of Wellfleet Harbor and the economy of Wellfleet.

Figure 1. Preliminary results of the National Marine Fisheries Service Fish Stock Climate Vulnerability Assessment for the Northeastern US (From Griffis 2015). Numbers indicated in each cell refer to number of species.



The purpose of this report is to summarize the Working Group's discussions related to the potential impacts of climate change and variability on shellfish resources in Wellfleet Harbor. Information about the Working Group, including its goals and members, can be found in Appendix A and at the project website: www.seri-us.org/content/fisheries-and-climate-Wellfleet. The Working Group used the Vulnerability, Consequences, and Adaptation Planning Scenarios (VCAPS) process to organize its discussions (Webler et al. 2014; an overview is provided in Appendix A).

Sea level rise

Relative sea levels are predicted to rise from several causes. Relative sea level rise in Wellfleet is predominantly a combination of rising ocean waters and land subsidence. Changes in sediment transport within the harbor may also affect relative sea level rise, by changing the amount of sand deposited on the bottom in different locations; this dynamic is not well understood but an on-going project by the Provincetown Center for Coastal Studies to map the Harbor bottom may provide useful baseline information (Mark Borrelli, personal communication, July 2015). An additional factor that may increase sea level rise in the northeastern US compared to other parts of the globe is the slowing of ocean currents (Burkett and Davidson 2012). In the northeastern US the combination of rising ocean waters and land subsidence is leading to higher relative sea level rise compared to many other coastlines in the US and elsewhere. Since 1900 the rate of sea level rise in the northeast has exceeded the global average by approximately 4 inches to about 1 foot in the Northeast versus about 8 inches globally over the past 110 years. The most recent assessments project a global sea level rise of 1-4 feet by 2100, with the northeast continuing to exceed global averages (Horton et al. 2014). These values are consistent with those reported in a recent report by the Commonwealth of MA, which estimated additional sea level rise of 8 to 16 inches by 2050 and 20 to 55 inches by 2100 (MA EOEA 2011). Sea level rise will impact embayments and marshes that support shellfish. According to the US Climate Science Program "degradation and loss of tidal marshes will affect fish and shellfish production in both the marshes themselves and adjacent estuaries (Titus et al. 2009, pg. 83).

Rising sea levels are associated with changes that can impact shellfish resources, including:

- Increasing salinity in estuaries by extending saltwater penetration upstream. Increased salinity has been linked to higher QPX mortality in clams (Dahl et al. 2012) and MSX infections in oysters (Ewart and Ford 1993).
- Loss of habitat, including important foraging and nursery habitat for some species (Najjar et al. 2010, Wong et al. 2014). Loss of habitat is due in part to submergence of coastal areas and increased erosion of coastlines in areas where the habitat and coastline cannot migrate landward like they would in a natural system (Frumhoff et al. 2007). This is especially important in terms of the loss of intertidal habitat. Loss of habitat will be exacerbated as sea level rises against armored shorelines that prevent the landward migration of intertidal flats and wetlands.
- An increase in the proportion of freshwater runoff into the Harbor from direct stream discharge, versus groundwater discharge, as coastal aquifers rise along with mean sea level. There is an increased risk of septic leachfields become inundated by rising sea and groundwater levels. A larger fraction of freshwater discharge will no longer pass through highly organic, anaerobic and, thus, denitrifying coastal sediments; in this way more nitrogen may be delivered to coastal waters to fuel eutrophication (Masterson and Portnoy 2005, Nuttle and Portnoy 1992).

Potential impacts to health of harbor, shellfish resources, and commercial shellfishing in Wellfleet Harbor from sea level rise.

Rising sea levels in Wellfleet Harbor may:

- *Change the proportion of inter-tidal and sub-tidal habitat areas*. Changes to the proportion of inter-tidal and sub-tidal habitat will impact the areas and techniques of growing both oysters and quahogs. An oyster that is continually submerged has the opportunity to feed longer than an oyster exposed at low tide but that oyster under water is also increasingly subject to sedimentation and burial as well as longer exposure to diseases, pests, and predators. There is some evidence that the food supply varies at different depths. At deeper depths food supply can be very restricted. Fishermen may need to change (and buy) gear to adapt to changing conditions.

- *Alter species' location and composition, including predators of shellfish as habitat type and availability shifts*.
- *Degrade water quality in Wellfleet Harbor*. Septic systems may fail as groundwater level rises to flood septic leachfields further inland. Furthermore, the route of freshwater discharge into Wellfleet Harbor will be altered with an increased surface flow into the Harbor. Consequently, less freshwater will flow through highly organic wetland, and intertidal and subtidal sediments, leading to less denitrification and bacterial removal. Because of development, marshes may not be able to migrate landward as sea levels rise. The consequent loss of marshes, which help to filter water, can exacerbate water quality problems in the Harbor.
- *Change how shellfish can be grown and harvested*. Rising sea levels will mean more grants are in deep water areas, such as those in Provincetown and Truro, thus requiring different methods of growing and harvesting over time.
- *Disrupt access to grants and lead to inadequacy of infrastructure.* Some shellfishermen in Wellfleet are already experiencing difficulties driving to their grants because of erosion, shoreline retreat, and access constraints. Rising sea levels (and coastal erosion associated with sea level rise) will exacerbate this problem. More moorings may be required if more shellfishermen need boats to work in deeper waters.
- *Lead to resource use conflicts.* Some gear used for deep water growing may lead to new conflicts among different users of the Harbor (e.g., with recreational boaters). Use of gear in deeper water has the potential to cause entanglements of marine mammals and sea turtles.

Changes in intensity and frequency of heavy precipitation

Across the continental US precipitation is falling in more intense events. This trend is especially strong in the northeastern US, which has seen a 71% increase in heavy precipitation events from 1958-2012 (defined as the heaviest 1% of all precipitation events in a year) (Karl et al. 2009, Mellilo et al. 2014, pg. 9). Furthermore, heavy precipitation events are expected to double in the Northeast by 2100 (Walsh et al. 2014), with a corresponding 10-15% increase in intensity (NECIA 2006). Coastal areas have the highest amounts of precipitation within the Northeast region (Melillo et al. 2014). Heavy precipitation events are associated with high winds and storm surge. High winds and storm surge can exacerbate coastal erosion. They may also cause damage to infrastructure.

Some of these heavy precipitation events will be in the form of hurricanes and winter northeasters. Furthermore, the number and power of severe storms is predicted to increase in the future, even as the overall frequency of storms may decrease (Bender et al. 2010). The intensity of hurricanes in the Atlantic will increase along with warming ocean waters: for each 1.8°F increase in tropical sea surface temperatures the rainfall rates of hurricanes could increase by 6-18% and the wind speeds of the strongest hurricanes could increase by about 1-8% (Field et al. 2012). Studies have found that there could be as much as a 50 percent increase in severe storm occurrences over the next century given the current rate of climate change (Dickerson 2013). However, there is considerable uncertainty about the exact character of changes along the coastal northeastern United States (Kirshen et al 2014).

Heavy precipitation events, particularly winter northeasters and hurricanes, are accompanied by storm surges, which can exacerbate near-shore flooding (Lin et al. 2012). A shallow slope will potentially produce a greater storm surge for the same storm than a steep shelf. Storm surge will have greater impact as sea levels rise, including a greater extent of inundation (flooding). The IPCC (Field et al. 2012) and US Global Change Research Program (Melillo et al. 2012, pg. 583) predict that flooding associated with 100 year storms (major storms that currently have a 1 percent chance of occurring, on average, in a given year) will become more frequent; in the northeastern US such flooding levels could occur as often as every 20 years in some locations. In addition to coastal erosion, storm surge can lead to changes in sediment transport dynamics within the harbor. Recent studies provide some information about sediment transport (Dougherty 2005) within the harbor but there is very limited understanding of how changes may impact shellfish in Wellfleet Harbor. For example, harbor bottoms on grants could rise, mitigating the impacts of sea level rise (Figure 2). Alternatively, changes could lead to suffocation of shellfish; in combination with changes in sediment transport dynamics, bluff erosion can lead to sand being deposited onto quahog beds. This may reduce harvestable areas and harvests of quahogs.

Seasonal variations are also expected. More winter precipitation will fall as rain, and less as snow (Frumhoff et al. 2007); this is due in part to warmer winter air temperatures. Under one of the climate change scenarios an average of 5%-20% increase in winter precipitation is expected by 2100 (Horton et al. 2014).

The predictions for seasonal precipitation used by the Commonwealth of MA (MA EOEA 2011) are shown in Table 1. The effects of these possible changes on shellfisheries are not well-understood. For example, while heavy precipitation events may decrease salinity levels in near-shore embayments, sea level rise may increase salinity levels. Thus, changes in salinity (and other aspects of water chemistry) may occur in pulses, having to do with the timing of tides and runoff from precipitation events.

Changes in precipitation patterns in coastal embayments, including flooding associated with severe storms, have been associated with:

- Reduced salinity in estuaries following high precipitation events, which can decrease biodiversity (Wong et al. 2014).
- Increased freshwater runoff into estuaries, which can lessen the prevalence of MSX infections among oysters (Ewart and Ford 1993) and QPX mortality in clams (Dahl et al. 2012), in contrast to increasing levels of salinity associated with rising sea levels.
- Increased pollution from run-off, septic systems, and wastewater treatment facilities, which can degrade estuarine water quality (Cocharane et al. 2009, MA EOEA 2011)
- Increased nutrient loading, which can lead to hypoxia and degradation of coastal ecosystems (Wong et al. 2014), including coastal salt marshes (Frumhoff et al. 2007), mortality of benthic animals (Najjar et al. 2010), and increased incidences of harmful algal blooms (Frumhoff et al. 2007). Larger or more frequent Harmful Algal Blooms can lead to increased closures of shellfishing beds, resulting in economic losses (Frumhoff et al. 2007).

- Increased stratification of estuarine waters with respect to salinity and temperature (Wong et al. 2014).
- Changes in sediment transport and coastal erosion, resulting from storm surge associated with heavy precipitation events.

Figure 2. Sediment transport in Wellfleet Harbor (Reproduced from Dougherty 2005, pg. 22).

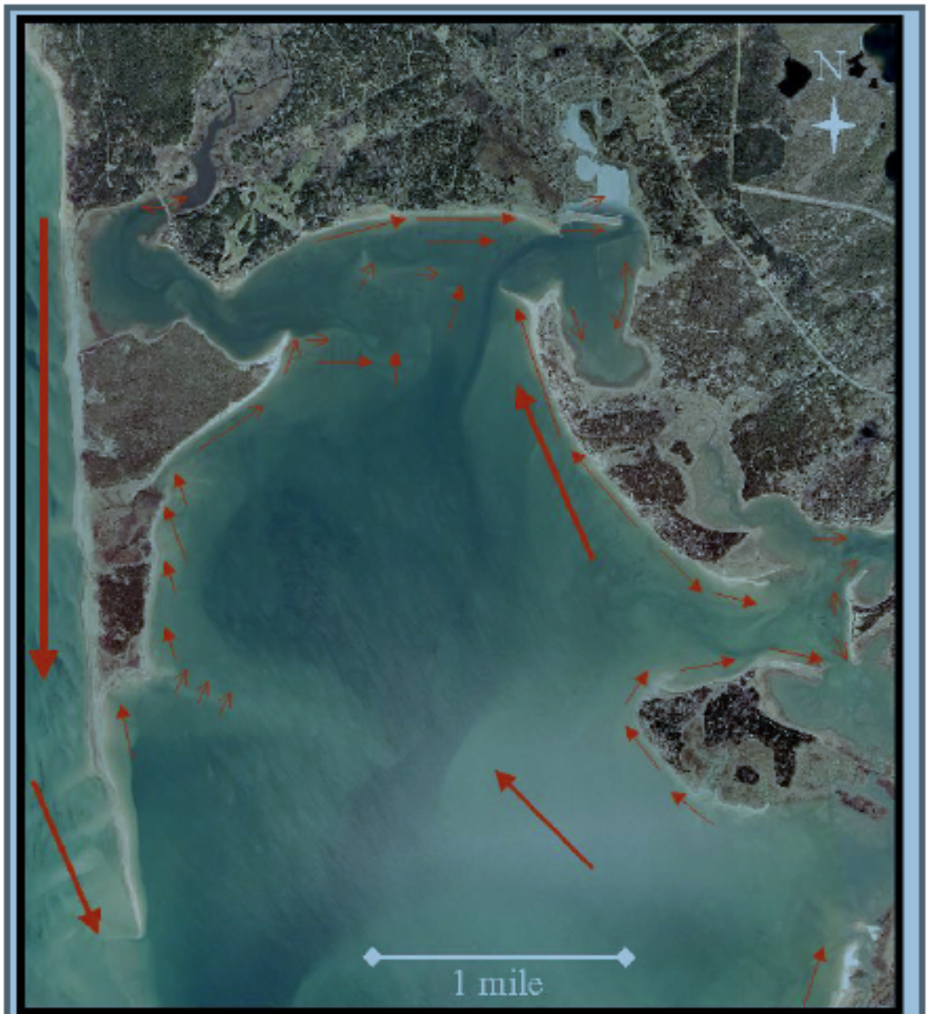


Figure 14: Composite sediment transport map constructed from bedforms exposed in various low tide air photos between the years of 1848 and 2003. The direction of the arrows indicates sediment movement and the size of the arrows correlates to the size of the sandwaves. The interpretations are identical when comparing this composite map to that constructed from the 1993 air photos. In fact, the intertidal bedforms identified in all of the archived aerial photographs appear almost identical throughout the various time frames. The apparent similarity through the years does not mean that the harbor is stagnant. Proof of this sediment moving into the harbor is the necessity to dredge the navigation channel that lies at the focal point for deposition. The apparent stationary nature of these bedforms indicates that the harbor has hit an equilibrium where most of sediment that is transported into the harbor builds the intertidal sandflats vertically, as opposed to lateral propagation, in order to keep up with sea-level rise.

Table 1. Predictions for seasonal precipitation used by the Commonwealth of MA (MA EOEA 2011).

	Current Conditions	2050 Prediction	2100 Prediction
Annual Precipitation	41 inches	43-44 inches (+5% to +8%)	44-47 inches (+7% to +14%)
Summer Precipitation	11 inches	11 inches (-1% to -3%)	11 inches (-1% to no change)
Winter Precipitation	8 inches	8.4-9.3 inches (+6% to +16%)	9-10.4 inches (+12% to +30%)

Potential impacts to health of harbor, shellfish resources, and commercial shellfishing in Wellfleet Harbor from changes in intensity and frequency of heavy precipitation.

- *Increase diseases and pathogens affecting both oysters and quahogs.*
- *Degrade water quality in Wellfleet Harbor.*
- *Disrupt access to grants from coastal erosion caused by severe storms and storm surge (in combination with rising sea levels).*
- *Decrease economic revenue due to increased pathogens, shellfish diseases, mortality and morbidity of shellfish, and harmful algal blooms.*
- *Alter sediment transport, which can impact the health of shellfish and alter suitability of grants for aquaculture.*

Warming water and air temperatures

Both air and water temperatures are expected to increase as a result of climate change. Predictions for how much temperatures will change are based on scenarios of greenhouse gas emissions. Uncertainties about potential changes to Gulf Stream circulation make these predictions challenging, because under some scenarios temperatures may decrease.

However, the current consensus is that both air and water temperatures will increase (Mellilo et al. 2014, MA EOEA 2011). An air temperature increase of 3-10 degrees F in the Northeast by 2080 is possible (Horton et al. 2014). These are annual averages, and the changes are expected to vary across seasons. Most of the warming will be experienced in the winter, rather than summer, months. Therefore, "the frequency, intensity, and duration of cold air outbreaks is expected to decrease" during this century (Horton et al. 2014, pg. 374). In the summer, the number of extreme heat days - those over 90 ^{o} F - are expected to increase, although the increase is likely to be less along the Cape than in other locations in the northeast. Furthermore, the character of heat waves is expected to change in the northeast, becoming more frequent, intense, and prolonged (Horton et al. 2014, pg. 374). Increases in air temperatures may impact the intensity of wind by changing temperature gradients. Higher winds can lead to more severe coastal erosion and sediment transport, which may impact shellfish resources.

Predictions reported in the 2011 assessment by the Commonwealth of MA (MA EOEA 2011) are shown in Table 2.

Table 2. Predictions reported in the 2011 assessment by the Commonwealth of MA (MA EOEA 2011).

	Recent Conditions (average of observed data over 1961–1990)	**2050 Prediction** (based on average of 2035–2064 predictions)	**2100 Prediction** (based on average of end-of-the-century predictions)
Annual Temperature	46° F	50° to 51° F	51° to 56° F
Summer Temperature	68° F	72° to 73° F	72° to 78° F
Winter Temperature	23° F	25° to 28° F	27° to 33° F

Sea surface temperatures are also predicted to rise, by up to 4 to 8 ° F by end of the century (Dutil and Brander 2003, Frumhoff et al. 2007, Nixon et al. 2004). The MA EOEA (2011) assessment reported an average annual sea surface temperature of 53° F in coastal MA waters, which may increase to 55-56° F by 2050 and 57-61° F by 2100. As a point of comparison, recent average summer (June – August) surface water temperatures at two monitoring stations in Wellfleet Harbor are shown in the Table 3 and the locations of the monitoring stations are shown in Figure 3. Table 4 provides average temperatures for 2008-2014 at the two monitoring stations in Wellfleet Harbor and a monitoring station in Cape Cod Bay, as an additional comparison.

Table 3. Surface water summer average temperatures (Fahrenheit) for Wellfleet Harbor (June - August). Data provided by Amy Costa, Provincetown Center for Coastal Studies, June 2015.

	Wellfleet Inner Harbor	**Wellfleet Outer Harbor**
Summer 2006	76.28	76.10
Summer 2007	72.32	71.96
Summer 2008	72.32	71.96
Summer 2009	71.42	71.24
Summer 2010	76.64	76.46
Summer 2011	74.66	74.48
Summer 2012	76.64	76.82
Summer 2013	75.02	74.66
Summer 2014	74.48	74.30

Figure 3. Location of Wellfleet Harbor surface water temperature monitors (by Provincetown Center for Coastal Studies).

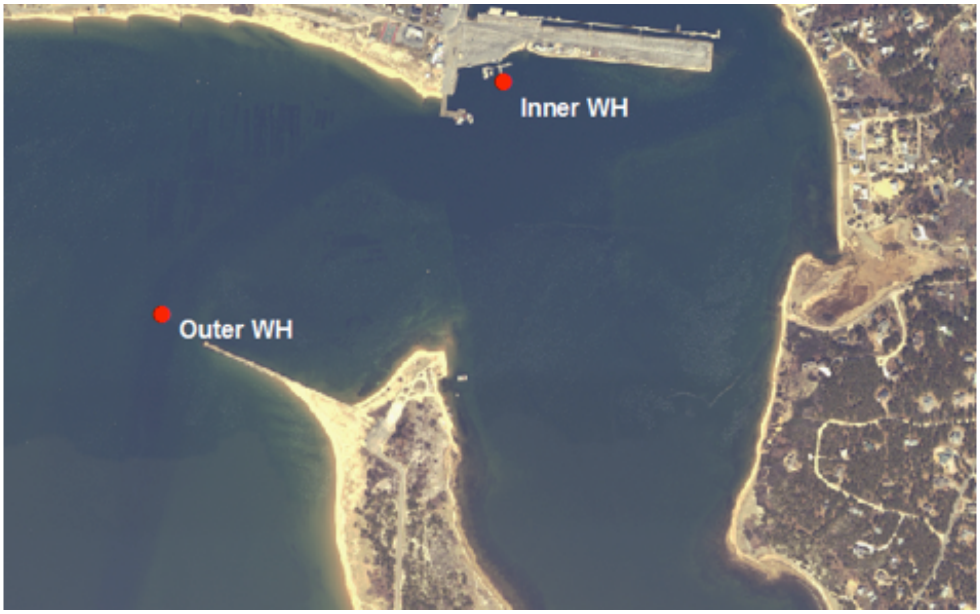


Table 4. Average surface water temperatures 2008-2014 (Fahrenheit). Data provided by Amy Costa, Provincetown Center for Coastal Studies, June 2015.

	Inner Wellfleet Harbor	Outer Wellfleet Harbor	Cape Cod Bay
May	64.83	64.25	54.23
June	70.50	70.43	63.06
July	77.53	77.12	70.54
August	75.46	75.23	70.55
September	68.98	68.96	68.15
October	61.66	60.57	59.02

A recent report by the Provincetown Center for Coastal Studies (Costa 2012) describes monitoring data results suggesting a slight warming trend of Cape Cod Bay water temperatures (pg. 17). This trend is consistent with observations of increases in coastal surface water temperatures in the Gulf of Maine (Nye 2010) and increases in the global mean in coastal surface water temperatures of about 1.25 ^{o} F (0.7°C) over the last century (Trenberth et al. 2007; Shearman 2010). The rate of increase also appears to be increasing. Between 1982-2006 sea surface temperatures in the Gulf of Maine increased by about 0.4 ^{o} F (0.23°C). However, the rate has increased in recent years (Belkin 2009).

Coupled with warmer winters, winter ice cover is predicted to decline (Frumhoff et al. 2007, Walsh et al. 2014), although there will be variation from winter to winter.

Warming will affect most trophic states and biological processes of coastal ecosystems (Canuel et al. 2012). Warming air and water temperatures may impact coastal embayments like Wellfleet Harbor in various ways:

- An increase in stratification of marine waters with respect to salinity and temperature (Doney et al. 2012)
- Depletion of oxygen levels (Falkowski et al. 2011, Keeling et al. 2010), primarily during higher summertime temperatures, and changes in nutrient availability (MA EOEA 2011). Higher temperatures also lead to higher metabolic rates (including photosynthesis and respiration) for ectothermic organisms, but this effect can be moderated by temperature tolerance, nutrient availability, and other biological processes. Higher temperatures can also lead to increased energy demand of organisms to keep up with increase metabolic rates (Doney et al. 2012). Shellfish in oxygen depleted waters may have greater resilience than finfish.
- A general decline in primary productivity (phytoplankon), with one source estimating a decline of 2-20% by 2100 (Steinacher et al. 2010).
- Warming may favor benthic predators feeding on bivalves (Philippart et al. 2003). Increased temperatures may favor growth rates of predatory crustacean species over prey bivalve species (Freitas et al. 2007).
- Rising sea temperatures may cause a decrease in the reproductive output of bivalve species (Philippart et al. 2003)
- Rising sea temperatures may advance the spawning season for bivalves leading to increased mortality due to decreased resource availability (phytoplankton as a food source) for spat – this is referred to as a mismatch in trophic synchrony within communities (Philippart et al. 2003, Brander 2010).
- Warming air and water temperatures may increase the presence of marine diseases (Harvell et al. 2002). For example, warmer temperatures may increase the spread of Dermo among oysters (Frumhoff et al. 2007) and may cause Dermo to become more prevalent farther north into New England states (Ford 1996).
- Warming air and water temperatures may increase the prevalence, seasonal period, and geographical range of human pathogens, including *Vibrio* (Daniels et al. 2000, Harvell et al. 2002, Kaspar and Tamplin 1993, Kelly 1982, Patz et al. 1996). Outbreaks of *Vibrio parahaemolyticus* (and other Vibrio spp.) have been associated with economic losses (Andrews 2012, Evans and Jones 2001, Keithly and Diop 2001, Martinez-Urtaza et al. 2010, McLaughlin et al. 2005, Sweeney 2013, Wessels et al. 1995).
- Some fish and invertebrates will shift north as their preferred temperature ranges shift north (Frumhoff et al. 2007, Mueter and Litzow 2008, Nye et al. 2009, Spencer 2008). Warming will likely lead to invasion of ecosystems by southern species that displace native species (Doney et al. 2012). Another issue is the increased potential for "biofouling" organisms that can clog oyster growing bags and trays and smother quahogs by clogging nets over quahog runs.

- Oysters are habitat forming species - they form oyster reefs. If they are harmed by pathogens, decrease in food and nutrients, etc. key habitat will be lost for other species (Doney et al. 2012).
- Warming air temperatures will alter temperature gradients, thus leading to changes in wind patterns and speeds. Higher winds can exacerbate coastal erosion and alter sediment transport in the harbor.

Potential impacts to health of harbor, shellfish resources, and commercial shellfishing in Wellfleet Harbor from warming air and water temperatures.

Warming air and water temperatures in Wellfleet Harbor may:

- *Increase diseases and pathogens affecting both oysters and quahogs and selectively benefit predator species.*
- *Increase shellfish mortality due to summertime oxygen depletions.*
- *Increase exposure risks to those who work the shellfish beds.*
- *Decrease formation of ice and allow predators and pathogens to over-winter.*
- *Decrease economic revenue due to increased pathogens, shellfish diseases, and harmful algal blooms.*
- *Decrease economic revenue due to reduced reproductive rates (MA EOEA 2011).*
- *Decrease economic revenue due to incidents of human pathogens (e.g., Vibrio parahaemolyticus) or to the imposition of new rules to reduce risks of outbreaks.*

Ocean acidification

Ocean chemistry is changing, and the main focus of attention has been ocean acidification, which occurs when increased CO2 uptake reduces available carbonate ions (Luttazi 2011). Recent projections suggest, under high emission scenarios, that global average pH could decrease from 8.1 to 7.8 by the end of the century (Melillo et al. 2014, pg. 48-49, Orr et al. 2005, Walsh et al. 2014). However, "Regional factors such as coastal upwelling, changes in discharge rates from rivers and glaciers, sea ice loss, and urbanization have created 'ocean acidification hotspots' where changes are occurring at even faster rates" (Mellilo et al. 2014, pg. 48). Other regions may experience slower or less severe changes, and nearshore and offshore pH levels may not be uniform. Higher levels of fluctuation nearshore may occur as a result of freshwater runoff rates and volumes. Some localized reports of decreasing pH in the northeast may be attributable to the effects of freshwater inputs (surface water runoff, which may increase as discussed above), but current data are insufficient to conclude this is a widespread, persistent condition throughout the northeastern US. This is anticipated to be a problem in, for example Maine. Effects of decreasing pH have been observed in the Pacific Northwest, which has generated increased awareness and study of this issue (Ekstrom et al. 2015, Feely et al. 2012).

The threat of ocean acidification is important for shellfish (Ekstrom et al. 2015, Cooley and Doney 2009). Shells of calcifying marine organisms can experience a decline in calcification rates (Gazeau et al. 2007, Hofmann et al. 2010, Kroeker et al. 2009, Luttazi 2011). Studies suggest that under conditions of declining pH bivalve shellfish exhibit slower growth rates, lower survival rates, lower lipid accumulation rates, thinner, malformed, or eroded shells, and potentially inhibited larval development of bivalve shellfish, and lower respiratory capacity of mollusks (Cooley et al. 2012, Doney et al. 2012, Talmage and Gobler 2010). Oysters and clams may be particularly vulnerable especially during the larval stage (Walsh et al. 2014). Overall, increased acidity can lead to a decline in some bivalve shellfish populations (Talmage and Gobler 2010). On the other hand, in areas of high productivity (such as Wellfleet Harbor), any increases in regional ocean water acidity may be offset by the alkalinity resulting from large populations and growth rates. Furthermore, experiments with the Eastern Oyster (*Crassostrea virginica*) in Chesapeake Bay "show that increases in temperature and high levels of salinity can reduce the impacts of lowering pH on calcification (Waldbusser et al., 2009)" (quote from Burkett and and Davidson 2012, pg. 133). Kroeker et al (2013a) provide an analysis suggesting increased sensitivity of some species to acidification when they are simultaneously exposed to elevated seawater temperatures. Such dynamics, and particularly how they will manifest in Wellfleet Harbor, are not well-understood.

Increased acidity of ocean waters can impact shellfish populations indirectly as well. For example, in Chesapeake Bay increased growth rates in crabs, tied to lower pH, can lead to increased predation of oysters (Fears 2013). Recent studies suggest that competitive interactions among species may shift, putting shellfish at a relative disadvantage (Kroeker et al. 2013b). Complex and indirect relationships also characterize the potential connection between ocean acidification and phytoplankton growth. Reduced nitrification, an effect of ocean acidification, could lead to reduced phytoplankton, thereby limiting a key food source for oysters (Beman et al. 2011). On the other hand, nitrification is inhibited by low pH (Henze et al. 1997), which suggests that low-pH may moderate any potential reduction in phytoplankton growth by increasing the availability of ammonium. Further, by inhibiting the formation of shell, ocean acidification may promote a general shift away from calcifier-dominated benthic ecosystems (Cooley et al. 2012).

By building oyster reefs, oysters are a habitat forming species. If they are harmed by ocean acidification (and pathogens), key habitat may be lost for other species (Doney et al. 2012) and ecosystem services may be disrupted (Cooley and Doney 2009, Cooley et al. 2012). For example, oyster reefs can also provide storm surge protection, and their loss can make shorelines more vulnerable to coastal erosion and damage.

Despite Wellfleet Bay's high rate of primary production, it may be particularly sensitive to the acidification of coastal waters because of anthropogenic disturbance to its fringing salt marshes. About half the coastal marshes around Wellfleet Harbor have been diked and drained since 1909. Salt marsh diking and drainage generates acid sulfate soils and the leaching of low-pH freshwater during ebb tides into the harbor (Soukup and Portnoy 1986, Portnoy and Giblin 1997). Oysters seaward of the Herring River dike currently show evidence of shell erosion, consistent with low pH and high rates of morbidity and mortality (Andrew Koch, Personal communication). Reduced buffering capacity of inflowing oceanic water from Cape Cod Bay could make the problem worse and more extensive, unless ongoing efforts in tidal restoration of the diked marshes succeed. Efforts to increase oyster populations to bolster ecosystem wide pH buffering may also help address the problem.

Potential impacts to health of harbor, shellfish resources, and commercial shellfishing in Wellfleet Harbor from ocean acidification.

The CCCE/WHSG/SEMAC WQ monitoring of sites in SE Massachusetts has not indicated any significant changes or trends in pH (Diane Murphy, personal communication). However, it is important to monitor for changes. Ekstrom et al. (2015) identify Massachusetts as having high social vulnerability to the impacts of ocean acidification because of the region's economic reliance on shellfish and other species that may be impacted. Their analysis also suggests that local manifestations of the impacts will not become significant until the 2nd half of the century, but this analysis has many uncertainties.

Ocean acidification has the potential to:

- *Decrease growth rates and survival rates of shellfish.*
- *Decrease economic value of shellfish and decrease revenue of shellfisherers.*
- *Change how shellfish can be grown and harvested*.

Conclusion

Climate stressors are expected to impact the northeastern US; coastal communities and ecosystems are particularly vulnerable. The climate stressors of most concern in the northeast are sea level rise, changes in intensity and frequency of heavy precipitation, rising water and air temperatures, and ocean acidification. High winds and storm surge will be associated with more intense storms, and can exacerbate impacts associated with sea level rise.

These impacts hold significance for shellfishing in Wellfleet Harbor, and, consequently, for the broader community. By impacting the health and value of shellfish, the community may experience reductions in tax revenues and license fees, etc. Local businesses may be impacted by a loss of local shellfish availability or quality. Yet, many questions remain. A number of factors may exacerbate or moderate potential impacts. For example, tidal influences and changes in runoff from precipitation events in Wellfleet Harbor may moderate water chemistry or temperature changes that may occur as a result of other climate stressors. High productivity of oyster and quahog aquaculture, coastal wetlands, and nearshore waters may moderate the local rate of ocean acidification. Zoning requirements may have an impact on shoreline changes. Environmental restoration projects, such as the restoration of the Herring River and Mayo Creek, may mitigate the more general effects of climate change by contributing to greenhouse gas sequestration, and help to buffer local water quality problems that could be exacerbated by climate change.

Long-term planning in Wellfleet should consider both local bio-physical features of the Harbor and local regulatory and policy programs to support adaptation in the face of climate change. Many options exist, and these are detailed in a companion report. On-going research and monitoring studies, such as monitoring of water quality in the Harbor and bottom mapping by the Provincetown Center for Coastal Studies and Sea Grant, can help inform assessment of options. The available information about how changes in sediment transport will impact shellfish habitat and growing is particularly sparse. Local experiences and knowledge will be essential to inform assessment and implementation of options to prevent, mitigate, cope, and recover from impacts associated with climate change. Planning for climate change impacts to shellfishing in Wellfleet Harbor will be the responsibility of multiple boards and committees in the Town. The Shellfish Advisory Board, Planning Board, Natural Resource Advisory Committee, Board of Health, Conservation Commission, Comprehensive Wastewater Management Planning Committee are among those whose recommendations, decisions, and actions can play an important role. The Wellfleet Selectboard will play a pivotal role in planning for climate change. Recommendations by Town Boards and Committees can be implemented only with the support of the Selectboard. Close coordination will be required to ensure that Wellfleet and the shellfishing sector are prepared to face the impacts of climate change.

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Appendix A: Overview of Working Group and the VCAPS process

The **purpose** of the Working group on Climate Change impacts on shellfishing in Wellfleet Harbor is to identify:

- threats to shellfishing in Wellfleet Harbor from climate change,
- the role of shellfish in mitigating impacts from climate change and other environmental hazards in Wellfleet Harbor, and
- strategies to increase the resilience of Wellfleet and its shellfishery in a time of climate change.

The **outcome** of the working group will be reports summarizing threats and opportunities, including specific actions that the Town and others can consider further to manage threats to the shellfishery in both the short and longterm. Specifically, the Working Group will provide information to inform local planning by addressing these questions:

1. What are anticipated impacts in Wellfleet Harbor and to shellfish from climate change?
2. To what extent do existing plans and proposed actions address impacts in Wellfleet Harbor and to shellfish from a changing climate? (Harbor Plan, Shellfish Management Plan, etc.)
3. What information is needed to understand impacts and how they can be managed (reduce vulnerabilities, adapt, etc.)?
4. What are additional / new actions that can be taken to reduce vulnerabilities and increase resilience of Wellfleet Harbor and its shellfish to a changing climate?

Members of the Working group on Climate Change impacts on shellfishing in Wellfleet Harbor

Barbara Brennessel, Janet Drohan, Mark Faherty, Curt Felix, Diane Murphy, John Portnoy, Jacob Puffer, Judy Taylor, Rebecca Taylor, Bob Wallace, and Patrick Winslow.

Additional assistance was provided by Greg Berman, Mark Borrelli, and Roxanne Smolowitz.

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Further information is available at: www.seri-us.org/content/fisheries-and-climate-Wellfleet

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