Climate Change Impacts on the Marine Environment in the Greater Boston Area

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Findings of the Greater Boston Research Advisory Group Report

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Acknowledgments

When the inaugural Boston Research Advisory Group (BRAG) report was released in 2016, it was recommended that the scientific consensus on climate change risk factors for Boston be updated every three to five years. The Barr Foundation made this update possible. Darci Schofield of the Metropolitan Area Planning Council (MAPC) had noted that the BRAG report offered essential information that was useful to and utilized by many cities and towns outside of the City of Boston and recommended a compilation of more localized information in the update. Subsequent discussions with Bud Ris, Mary Skelton Roberts, Emily Sidla, and Kalila Barnett of the Barr Foundation led to the expansion of the study area to include the 101 towns and cities within the MAPC region. We also acknowledge Ms. Schofield for helping to recruit members of the GBRAG steering committee and to organize our outreach activities within the MAPC domain. This special report is a result of those outreach activities as the impacts of climate change on the marine environment was mentioned as a major concern across the region.

We acknowledge and appreciate the guidance and support we received from John Cleveland and Amy Longsworth of the Green Ribbon Commission in launching the GBRAG. We gratefully acknowledge the Barr Foundation for funding the GBRAG activities and reporting. We also gratefully acknowledge the competent and steadfast administrative efforts of Kimberly Starbuck of the Urban Harbors Institute at UMass Boston, who organized and managed GBRAG meetings, communications, and the GBRAG report. We further acknowledge the members of the GBRAG Steering Committee for their time and thoughtful feedback during this process. We also greatly appreciate the thorough review of this report and detailed feedback provided by Drs. Bhaskaran Subramanian and Mike R. Johnson.

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Executive Summary

1. Introduction

Following the success of the inaugural Boston Research Advisory Group (BRAG) report (Douglas et al., 2016), it was decided to expand the domain of the BRAG to include the 101 communities within the Metropolitan Area Planning Council (MAPC) region, renaming the effort the Greater Boston Research Advisory Group (GBRAG). Further it was decided to present information to the MAPC region in a way that is relevant for communities struggling to plan for our changing climate. A coordinated outreach to the GBRAG communities was undertaken that included online surveys and in-person interviews. The results of this outreach were compiled into a list of risk factors of most concern and interest to the MAPC communities and for which data, or design values, would need to be collected to prepare for these climate change risk factors. The outreach effort identified a previously unassessed risk factor, namely changes in the marine environment, which was deemed of great concern to communities in the MAPC region, specifically those communities bordering the coastline.

The marine environments of interest to GBRAG communities extend from the near shore tidal flats, across the shallow waters along the Massachusetts coastline, and out into the deeper waters of the North Atlantic. These waters overlay Georges Bank to the south and east of Massachusetts, the Gulf of Maine to the north as well as the Scotian Shelf further north. The physical properties of the waters in these regions are dramatically affected by two major large-scale current systems—the northward flowing Gulf Stream that brings warm, saline water from the subtropics, and the southward flowing Labrador Current that brings cold, fresh water from the subarctic. They are also affected by smaller scale currents such as the Maine coastal current, which flows southwestward along the coastline from Maine to Massachusetts, and by deep water currents arriving from the south as part of the Gulf Stream and from the north, both of which flow through the Northeast Channel into the Gulf of Maine. Finally, the physical properties are modulated by onshore processes as well, such as riverine outflow and cold (and warm) air transport from off the continent.

Assessing future change in the marine environment is exceptionally challenging because risk factors involve a complex interplay of not just physical processes and parameters, but also chemical, geological, and biological ones as well. The Domain of the marine environment that covered a coherent set of risk factors were identified as the following:

- Changes in the Physical Environment
- Changes in Water Quality
- Changes in Coastal Conditions
- Changes in Ecological Conditions

2. Changes in the Physical Environment

Key changes in Physical Environment Design Values (ocean temperature, salinity, ocean currents/circulation)

- Over the last few decades, the waters off the coast of Massachusetts have warmed more than almost anywhere in the world (Pershing et al., 2015). This warming is expected to continue over the next 30 years, with an additional surface warming of 1.0 °C to 2.5 °C across most of the domain by 2050 and up to 4 °C by 2100 (Saba et al., 2016; Caesar et al., 2018).

- All model simulations indicate a near surface warming of 1.0 to 2.5 °C by 2050 under high emissions scenarios and a potential warming of 2 to 4 °C by 2100; however, the underlying mechanism for this warming differs by model.
- Marine heat waves pose substantial threats to the ecology and ecosystems of marine environments in our region (Mills et al., 2013). In 2012, ocean temperatures off the coast of Massachusetts and in the Gulf of Maine were the warmest ever observed (Pershing et al., 2015). Temperatures have remained at near-record levels in this region for the last 5 years.
- Recent research suggests that the 2012 marine heat wave, whose intensity was a 1-in-a-10,000 year event, may become a once in a decade event if global mean temperatures rise above 2 °C (equivalent to the temperature increase by 2050 under current emissions). If global mean temperatures rise above 3 °C, this event could potentially occur every 1 to 2 years.
- Historically, the surface waters around Massachusetts have become less saline; combined changes in surface salinity and temperature have reduced vertical mixing of nutrient rich deep water into the photic zone (Henson, 2007; Agusti and Duarte, 1999). The water at depth is expected to continue to increase in salinity. However, near the surface, changes in salinity are not well constrained.
- At the surface, expected salinity changes range from +/-0.1 psu (GoM Study, 2019) by 2050, and the difference expands by the end of the century to +/-0.3 psu (Alexander et al., 2020). At depth, most simulations show an increase in salinity of ~0.1 to 0.2 psu by 2050. However, as time progresses, salinity changes become more uncertain and range from ~+/-0.2 by 2100.
- Recent research indicates the possibility that the Gulf Stream circulation feature may stay relatively stationary or even move further south (Alexander et al., 2020; Shin et al., 2020). At the same time, the near-shore circulations, particularly those in the Gulf of Maine, are expected to intensify.
- The Gulf Stream has begun to noticeably weaken and broaden in response to a slowdown of the Atlantic Meridional Overturning Circulation (AMOC) (McCarthy et al., 2018), resulting in substantial warming over the southern portion of the domain as the warm subtropical waters diffuse northward into our region, as well as into the Gulf of Maine.
- The largest data gap regarding our knowledge and understanding of changes in temperature, salinity and near surface and subsurface currents affecting the marine environments of interest to GBRAG communities is the lack of high-resolution simulations of the waters off our coasts.

3. Domain: Changes in Water Quality

Key changes in Water Quality Design Values (ocean pH, water quality conditions, amount and type of pollutants and impact of pollutants on habitats)

- Coastal acidification is a response to biological respiration, precipitation and evaporation dynamics; riverine loads of carbon species; long-term variability due to climate change-induced increases of atmospheric CO_2; and circulation patterns delivering low pH water from adjacent sources in the Gulf of Maine (Wang et al., 2020, 2017). The GBRAG nearshore area is likely to see further reductions in pH (Feely et al., 2009). Reductions in eutrophication in coastal ocean environments will help by preventing synergistic drops in pH associated with larger regional patterns that drive down pH.
- The interaction between local and regional patterns of pH is not well constrained in Boston Harbor and Massachusetts Bay because lower pH conditions result from the interaction of multiple stressors. Some harmful algal bloom related species in the Gulf of Maine have been shown to have decreased growth with lower pH (Seto et al., 2019); how changes in the community structure impact harmful algal bloom (HAB) patterns and impacts in GBRAG nearshore environments remains an open question.
- Since 1984, $8.5 billion (USD) have been spent to reduce the nutrient addition to Boston Harbor (MWRA, 2019), and the desired restorative effect managers envisioned has been observed with decreased pelagic primary production (Oviatt et al., 2007), reduced summer phytoplankton biomass

(Taylor et al., 2011), reduced benthic metabolism (Tucker et al., 2014), increased seagrass coverage (Taylor et al., 2020), and increased health in Boston Harbor flounder (Moore et al., 2018a).

- The City of Boston has added approximately 70,000 residents over the last decade and projects a similar growth in population over the next decade, which could result in an annual increase of 1.2 billion gallons of additional wastewater treated and discharged to Massachusetts Bay.
- The addition of greenhouse grown cannabis poses a risk as a new agricultural nutrient load and has been shown to increase nutrient concentrations in adjacent rivers, increasing concentrations of dissolved phosphorus and nitrate by 28-fold and 8-fold, respectively (Maguire et al., 2018). The sudden increase of greenhouse-derived nutrients in the rivers delivering water to the nearshore GBRAG area could have severe impacts to phytoplankton biomass and community structure, reversing the gains made by redirecting wastewater discharges offshore.
- Projections are needed to determine how changes in precipitation within GBRAG watersheds will affect nearshore water quality. There is no estimate for future shifts in the nutrient composition of the nearshore environment with increased population.
- Since the 1980s, pollutants stemming from industrial point sources, wastewater discharges and non-point inputs have been reduced; however, threats stemming from legacy contamination from persistent organic pollutants and continued non-point sources of petroleum associated with impervious land use in watersheds (Blalock et al., 2020). Within the water column, petroleum products pose the largest contemporary threat.
- While mussel tissue has shown decreases in chemical contamination within Boston Harbor (Hunt and Slone, 2010), blue mussels within the inner portions of Boston Harbor exhibit biomarkers indicating stress from Polychlorinated biphenyls (PCBs), likely from the legacy of poor water quality (Blalock et al., 2020). The impact of anthropogenic pharmaceuticals (e.g., caffeine, estrogen) on biota is a relatively new topic, and not well understood, but emerging research suggests a number of potential physiological impacts, including impacts to reproductive success (Ojemaye and Petrik, 2019; Gaw et al., 2014).
- Resuspension of legacy metals (Kalnejais et al., 2010) and PCB contamination due to either storms or dredging will be a consistent issue in the future. Projected increases in river flows could resuspend riverbed sediment and deliver higher chemical pollutant loads from flushed watersheds.
- Because ocean acidification potentially increases the toxicity of metals to certain phytoplankton species (Dong et al., 2020), there needs to be a clear idea of what synergistic effects changing pH and increased metal concentration have on primary producer communities. The longer-term impacts of pharmaceuticals on marine biota is poorly understood and, particularly in densely populated urban waters such as the GBRAG region, warrants the establishment of region-specific long-term monitoring efforts.
- While the majority of Boston Harbor subtidal habitat is naturally unvegetated, eelgrass biomass within Boston Harbor has almost doubled since 1994 (Taylor et al., 2020). Boston's salt marshes have been reduced by 81% since 1777 (Bromberg and Bertness, 2005), however marshes continue to exist either at undeveloped coastal sites or as fringes around the river mouths. These habitats are under threat from pollution from plastics/microplastics and pharmaceuticals.
- Microplastic pollution in Boston Harbor is likely preferentially collected in subtidal eelgrass beds (Huang et al., 2020), reducing the number of species found in bivalve reefs (Green, 2016), and accumulating in mussel tissues (Von Moos et al., 2012). Salt marshes are impacted by microplastics and accelerate microplastic contamination from the degradation of macroplastic accumulated in the marsh (Weinstein et al., 2016).
- Reestablished eelgrass and shellfish beds within Boston Harbor will be impacted by increased plastic fouling and increased concentrations of microplastic debris in marine sediments associated with more people living within the upgradient watershed. The growing population within the Massachusetts Bay

watershed will also increase the load of pharmaceuticals and pharmaceutical by-products discharged from treated wastewater. Impact to habitats under the current urban growth paradigm will be an issue of growing importance to GBRAG nearshore restoration and recovery.

- There is no doubt that pharmaceuticals will continue to be a constituent of wastewater. The next planning step should be to determine if there are infrastructure or operational solutions which could establish controls on pharmaceuticals in wastewater. Additionally, there needs to be a systematic quantification of microplastic pollution within Boston Harbor.

4. Changes in Coastal Conditions

Key changes in Coastal Condition Design Values (extent/condition of natural shorelines and habitats, extent and condition of armoring and extent/condition of living shorelines):

- Twenty-seven percent of ocean-facing shorelines have been armored (MA CZM, 2013), compared to the national average of 14% (Gittman et al., 2014). Armoring rates in many developed areas of the GBRAG region are much higher, including 58% in Boston Harbor, 46% in North Shore, and 44% South Shore. Suffolk county was highlighted as among the most armored counties in the nation at 94%.
- While nature-based approaches to shoreline management, often termed “living shorelines,” have become increasingly popular alternatives to shoreline armoring, they have been less common in Massachusetts. However, example projects do exist and provide case studies for planning and considering potentially “greener” trajectories of shoreline change than traditional armoring.
- Nationally, shoreline armoring is projected to double by 2100 (Gittman et al., 2014). Increases in armoring may be less dramatic in MA due to lower population growth estimates and a stricter regulatory environment than some other states; however, permitting and regulatory concerns may also impede the implementation of living shorelines.
- Critical questions for addressing future shoreline change in the Commonwealth and the potential impacts for ecosystems and coastal communities include: What are the biophysical and ecological factors limiting the potential success of natural shorelines in coastal MA? What are the social and regulatory barriers to nature-based and living shorelines in coastal MA?

5. Changes in Ecological Conditions

Key changes in Ecological Conditions Design Values (populations of marine life, extent of marine algae/eelgrass, number and extent of algal blooms and fish catch):

- In general, commercial quotas and catches of major commercial species have been roughly stable over the last two decades, with some species increasing, and others declining (MADMF, 2020). Rapid warming in the Gulf of Maine has negatively impacted species at the lower end of their range, such as Atlantic cod (*Gadus morhua*), yellowtail flounder (*Limanda ferruginea*), and northern shrimp (*Pandalus borealis*), whereas it has promoted the northern expansion of more southerly species such as black seabass (*Centropristes striata*) and blue crabs (*Callinectes sapidus*). Increased temperatures have likely decreased the productivity of stocks of key fisheries species that thrive in colder waters such as Atlantic cod (Pershing et al., 2015) and has induced species like the American lobster (*Homarus americanus*) to shift their range northward (Pinsky et al., 2013).
- As the climate continues to shift, it would be reasonable to expect fish communities in Massachusetts to follow the same trend, which would mean decreases in population for cold water associated species such as winter flounder, American lobster, silver hake, and Atlantic herring, and corresponding increases in warm water associated species such as summer flounder, black seabass, blue crab, scup and butterfish (Howell and Auster, 2012).

- The primary data gaps involve our understanding of how localized conditions will change in response to the complex changes in physical, chemical, and biological parameters resulting from climate change in the greater Gulf of Maine Large Marine Ecosystem (LME). Understanding the impact of recent efforts to restore and protect critical nearshore habitats (saltmarsh, eelgrass, access to riverine habitats for anadromous species, shellfish habitat) on fish population dynamics is a critical and ongoing data gap to predicting future trends in fish abundance and fisheries landings.
- Although sewage discharge has been substantially ameliorated, it remains a significant concern, and current treatment approaches are at or near the limit of technological feasibility. There is tremendous uncertainty associated with riverine and non-point nutrient loads. Projections are needed to estimate how changes in precipitation within GBRAG watersheds will impact coastal water quality.
- Recent modeling efforts suggest substantial potential increases in cyanobacteria blooms in coastal freshwaters of the Northeast, with frequency of cyanobacterial blooms potentially forecast to increase by 200 to 300% by 2050 (Chapra et al., 2017).
- Hare et al. (2016) conducted a climate vulnerability assessment of 82 fish and invertebrate species on the Northeast U.S. continental shelf and found that vulnerability is high or very high for half of the species, whereas some will increase their productivity and/or distribution in the Gulf of Maine.
- Marine benthic algal and eelgrass habitats are among the many coastal habitats that are extremely vulnerable to anthropogenic impacts and have been degraded globally (Orth et al., 2006). The Massachusetts Department of Environmental Protection documented a 42% decline in seagrass extent between 1996 and 2006 in Boston Harbor (Leschen et al., 2010); yet, improved water quality, natural recovery, and restoration efforts resulted in a 50% expansion in seagrass habitat throughout the harbor between 2006 and 2016 (Evans et al., 2018) despite some setbacks in the region (Bowen et al., 2019).
- Kelp forests near Boston will likely transition to less desirable ecosystem states. Meanwhile, efforts to increase the water quality of Boston Harbor and the Charles River have likely increased the quality and quantity of seagrass habitat in the coastal waters around Boston (Bowen et al., 2019).
- In many areas, seagrass restoration may be necessary to restore seagrass beds; yet, seagrass restoration has generally been challenged by low success rates (Bayraktarov et al., 2016). Therefore, efforts to investigate how to increase the effectiveness of seagrass restoration methods (e.g., plant source, planting density, etc.) are merited.

1. Introduction

Following the success of the inaugural Boston Research Advisory Group (BRAG) report (Douglas et al., 2016), it was decided to expand the domain of the BRAG to include the 101 communities within the Metropolitan Area Planning Council (MAPC) region, renaming the effort the Greater Boston Research Advisory Group (GBRAG). Further it was decided to present information to the MAPC region in a way that is relevant for communities struggling to plan for our changing climate. To facilitate the latter effort, a coordinated outreach to the GBRAG communities was undertaken that included online surveys and in-person interviews. The results of this outreach were compiled into a list of risk factors of most concern and interest to the MAPC communities and for which data, or design values, would need to be collected to prepare for these climate change risk factors.

While many of the identified risk factors were ones previously assessed in the inaugural BRAG report, the outreach effort identified a previously unassessed risk factor, namely changes in the marine environment, which was deemed of great concern to communities in the MAPC region, specifically those communities bordering the coastline. To proceed with an assessment of the changing marine environment, we were tasked with first surveying the outreach results to identify the Domains of the marine environment that covered a coherent set of risk factor topics. The Domains that were identified were the following:

- Changes in Physical Environment
- Changes in Water Quality
- Changes in Coastal Conditions
- Changes in Ecological Conditions

For each of these Domains, we were further tasked with identifying the relevant Design Values needed to be assessed. Based upon the feedback from the community outreach efforts, as well as our own expert knowledge of feasible targets for assessment, we identified the following Design Values:

Changes in the Physical Environment Design Values

- Changes in ocean temperature
- Changes in ocean salinity
- Changes in ocean currents/circulation

Changes in Water Quality Design Values

- Changes in ocean pH levels
- Changes in water quality condition
- Changes in amount and type of pollutants in water
- Impact of pollutants on habitats

Changes in Coastal Condition Design Values

- Changes in extent/condition of natural shorelines and habitats
- Changes in extent/condition of armoring
- Changes in extent/condition of living shorelines

Changes in Ecological Conditions Design Values

- Changes in populations of marine life
- Changes in extent of marine algae/eelgrass
- Changes in number and extent of algal blooms
- Changes in fish catch

Unlike for other risk factors, assessing future change in the marine environment is exceptionally challenging because they involve a complex interplay of not just physical processes and parameters, but also chemical, geological, and biological ones as well. That said, the following document provides our expert assessment of the state of the science concerning expected changes in marine environment relevant to communities in the MAPC region.

2. Domain: Changes in the Physical Environment

2.1 OVERVIEW

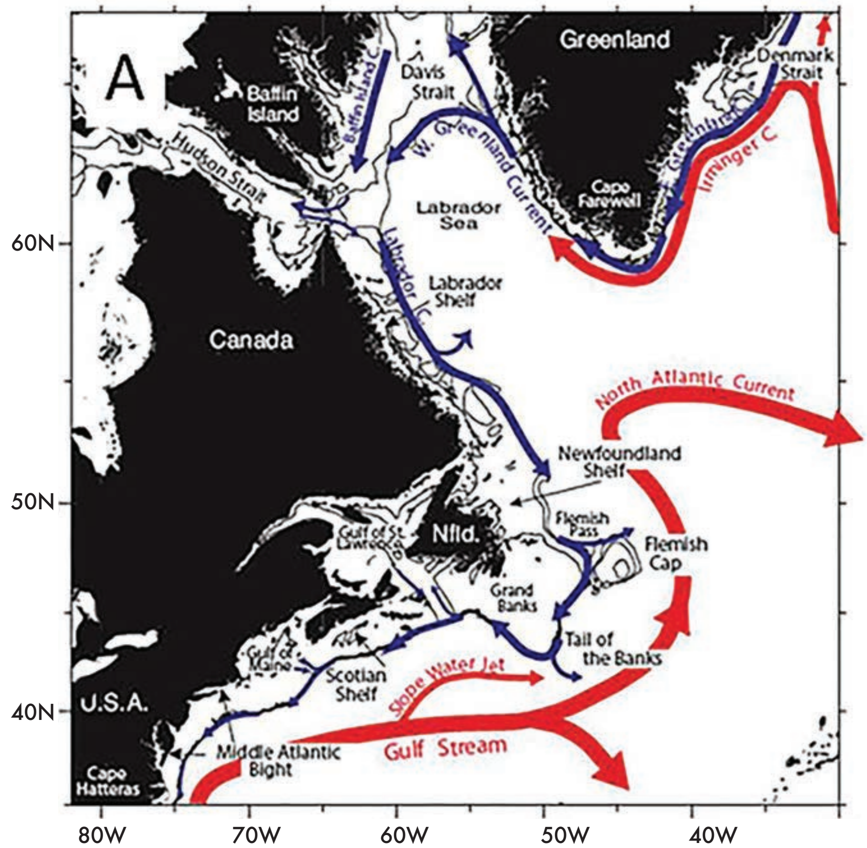
The marine environments of interest to GBRAG communities extend from the near shore tidal-flats, across the shallow waters along the Massachusetts coastline, and out into the deeper waters of the North Atlantic. These waters overlay Georges Bank to the south of Massachusetts, the Gulf of Maine to the north, as well as the Scotian Shelf further north. The physical properties of the waters in these regions are dramatically affected by two major large-scale current systems (see Figure 1, page 9)—the northward flowing Gulf Stream which brings warm, saline water from the subtropics, and the southward flowing Labrador Current which brings cold, fresh water from the subarctic. They are also affected by smaller scale currents such as the Maine coastal current, which flows southwestward along the coastline from Maine to Massachusetts, and by deep water currents arriving from the south as part of the Gulf Stream and from the north, both of which flow through the Northeast Channel into the Gulf of Maine. Finally, the physical properties are modulated by onshore processes as well, such as riverine outflow and cold (and warm) air transport from off the continent.

To properly estimate changes in the physical environmental conditions (both in the coastal oceans and open seas) requires capturing a range of these oceanic and atmospheric processes. To do so, the scientific community has recently turned to the use of computer-generated models of the oceanic, atmospheric, and land-surface state, referred to as Earth System Models (ESMs). While most of these are global in scale, and hence cannot adequately differentiate between near-shore and open water conditions, the advent of regional ocean models (ROMs) that represent much more nuanced conditions and can be forced with the global scale models have allowed scientists to better represent both the historical and future state of the marine environment along the Massachusetts coastline. As part of this assessment, we will turn to these with a focus on three key physical parameters, or "design values" of interest, namely temperature, salinity, and patterns of circulations.

2.2 KEY FINDINGS

- Over the last few decades, the waters off the coast of Massachusetts have warmed more than almost anywhere in the world (Pershing et al., 2015). This warming is expected to continue over the next 30 years, with an additional surface warming of 1.0 °C to 2.5 °C across most of the domain by 2050 and up to 4 °C by 2100 (Saba et al., 2016; Caesar et al., 2018).
- All simulations indicate a near surface warming of 1.0 to 2.5 °C by 2050 under high emissions scenarios and a potential warming of 2 to 4 °C by 2100; however, the underlying mechanism for this warming differs by model.
- Marine heat waves pose substantial threats to the ecology and ecosystems of marine environments in our region (Mills et al., 2013). In 2012, ocean temperatures off the coast of Massachusetts, and in the Gulf of Maine were the warmest ever observed (Pershing et al., 2015). Temperatures have remained at near-record levels in this region for the last 5 years.

Figure 1
General circulation of the western North Atlantic.



The thick red arrow along the bottom of the figure represents the warmer waters of the Gulf Stream from the south and the thinner blue arrow along the coast of Canada represents the colder waters of the Labrador Current from the north.

Source: Fratantoni and Pickart, 2007 (© American Meteorological Society. Used with permission.)

- Recent research suggests that the 2012 marine heat wave, whose intensity was a 1-in-a-10,000 year event, may become a once in a decade event if global mean temperatures rise above 2 °C (equivalent to the temperature increase by 2050 under current emissions). If global mean temperatures rise above 3 °C, this event could potentially occur every 1 to 2 years.
- Historically, the surface waters around Massachusetts have become less saline; combined changes in surface salinity and temperature has reduced vertical mixing of nutrient rich deep water into the photic zone (Henson, 2007; Agusti and Duarte, 1999). The water at depth is expected to continue to increase in salinity. However, near the surface, changes in salinity are not well constrained.
- At the surface, expected salinity changes range from +/-0.1 psu (GoM Study, 2019) by 2050, and the difference expands by the end of the century to +/-0.3 psu (Alexander et al., 2020). At depth, most simulations show an increase in salinity of ~0.1 to 0.2 psu by 2050. However, as time progresses, salinity changes become more uncertain and range from ~+/-0.2 by 2100.
- Recent research indicates the possibility that the Gulf Stream circulation feature may stay relatively stationary or even move further south (Alexander et al., 2020; Shin et al., 2020). At the same time, the near-shore circulations, particularly those in the Gulf of Maine, are expected to intensify.

- The Gulf Stream has begun to noticeably weaken and broaden in response to a slowdown of the Atlantic Meridional Overturning Circulation (AMOC) (McCarthy et al., 2018), resulting in substantial warming over the southern portion of the domain as the warm subtropical waters diffuse northward into our region, as well as into the Gulf of Maine.
- The largest data gap regarding our knowledge and understanding of changes in temperature, salinity and near surface and subsurface currents affecting the marine environments of interest to GBRAG communities is the lack of high resolution simulations of the waters off our coasts.

2.3 CHANGES IN TEMPERATURE

Review of existing science

The surface waters in the Gulf of Maine have recently warmed more than almost anywhere else in the world and are now 1.5 °C warmer than at the start of the 21st century (Pershing et al., 2015). This surface warming has been more pronounced in the warm months than the cold months because the stability of the water column in the warm months prohibits mixing with the cooler waters at depth (Thomas, 2017; Friedland, 2020). This has extended the warm water season at the expense of the cold water season by 1 to 2 days per year over the last 30 years (Thomas, 2017). Historically, waters at depth have been warming as well with the greatest warming also found during the warm season (Friedland, 2020). In most cases the warming of the bottom water is smaller than that found at the surface, with a main exception being along the southern Massachusetts coastline extending out to Martha's Vineyard and Nantucket (Friedland, 2020). The main explanation for the warming both near the surface and at depth has been a northward shift and slowing of the Gulf Stream, which has allowed warm, subtropical waters to extend further up the coastline, as well as into the Gulf of Maine (Caesar et al., 2018).

Marine heat waves—periods of extremely high ocean temperature—also pose substantial threats to the ecology and ecosystems of marine environments in our region (Mills et al., 2013). Indeed, in 2012, ocean temperatures off the coast of Massachusetts, and in the Gulf of Maine in particular, were the warmest ever observed (Pershing et al.,2015) and were estimated to be a one-in-a-10,000 year event (Laufkötter et al., 2020). That said, temperatures have remained at near-record levels in this region for the last five years, with another marine heat wave affecting the region in 2016 that was only slightly less intense than the 2012 event, and another reached similar levels in 2018. Such exposure to these types of long-lived hazards is particularly acute for marine ecosystems, which may be resilient to singular extreme events, but destabilize under chronic exposure to multiple events (Kilduff et al., 2015; Mantua, 2015).

Projections

Initial projections using one of the first high resolution ROMs (Saba et al., 2016), which simulated conditions equivalent to the current RCP4.5 radiative forcing for the year 2100, suggest substantial changes in both surface and subsurface temperatures in the near-shore regions of Massachusetts, with greatest warming in the Gulf of Maine. In addition, the largest warming (>8 °C) was at depth, while the warming at the surface was 3 to 4 °C. In these early simulations, the warming was attributed to the replacement of cold, fresh Labrador sea water with warm, saline subtropical water as the Gulf Stream continued to weaken and shift northward. More recent simulations using a greater range of ESMs and ROMs suggest a more nuanced response. In one set of experiments using the RCP8.5 radiative forcing inputs to a ROM, it was found that temperatures at the surface and subsurface increased approximately 3 to 4 °C by 2100, despite the fact that the Gulf Stream showed a pronounced *southward* shift by the end of the century. In this case, the warming was attributed to the intrusion of subarctic water which, while cold, warms more over the coming century than the mid-latitude waters off the coast of Massachusetts, hence it serves to amplify the temperature increase that is occurring locally. Additional model runs show similar discrepancies. All indicate a near surface warming of 1.0 to 2.5 °C by 2050 under high emissions scenarios and a potential warming of 2 to 4 °C by 2100. However, the underlying mechanism for this warming differs across models, with some indicating the canonical influence of warm, subtropical waters, others indicating the influence of amplified arctic warming intruding along the Labrador current, and others suggesting a role for amplified warming of the continental interiors influencing the near surface ocean temperatures through transport by the westerly winds that prevail at these latitudes (Alexander et al., 2020).

In addition to changes in the mean state of the ocean temperatures, recent research has also investigated the frequency and duration of marine heat waves in the region (Laufkötter et al., 2020). The characteristics of these marine heat waves are a function of the overall change in global mean temperatures, as well as the local augmentation of that heating as discussed above. Recent research suggests that the 2012 marine heat wave, whose intensity was a 1-in-a-10,000 year event, may become a once in a decade event if global mean temperatures rise above 2 °C (equivalent to the temperature increase by 2050 under current emissions). If global mean temperatures rise above 3 °C, this event could potentially occur every 1 to 2 years. Similar results hold when considering the duration of the event, which initially was a 1-in-a-100 year event but could occur once every 5 years (under a 2 °C warming) or potentially every year (under a 3 °C warming).

Open questions and data gaps

The largest data gap regarding our knowledge and understanding of changes in near surface and subsurface temperatures of the marine environment affecting GBRAG communities is the lack of high-resolution simulations of the waters off our coasts. As more simulations have been performed for this region, the expected response has become less constrained, not more so. The range in uncertainty is a function of uncertainties in the large-scale warming of the planet as a whole, uncertainties in the internal variability of the North Atlantic dynamics and thermodynamics that can modulate the global warming signal, as well as uncertainties in the dynamic and thermodynamic response of both large-scale and local currents in this region. These in turn are amplified by uncertainties in the atmospheric drivers of these currents, including shifts in large scale wind fields as well as shifts in the strength of the AMOC, both of which control the strength and positioning of the Gulf Stream and Labrador currents, as well as the near-shore currents such as the Maine Coastal Current. Hence, substantially more simulations with different global ESMs and different regional ocean models will be needed to better represent the potential range of temperature change in our local marine environments.

2.4 CHANGES IN SALINITY

Review of existing science

While there is a strong long-term trend in the surface temperatures off the coast of Massachusetts, the signal is not as robust for salinity. This lack of distinct trend results from the strong multi-decadal variations that have occurred historically in this region (Bisagni, 2016; Harden et al., 2020; Drinkwater and Gilbert, 2004; Wallace et al., 2018). There is consensus that surface salinity both in the northern and southern portions of the domain decreased dramatically during the 1990s (Drinkwater and Gilbert, 2004; Bisagni, 2016) as a result of the intrusion of cold, fresh water along the Labrador current. However, since then, little detectable trend has been found either in the Gulf of Maine or Georges Bank (Wallace, 2018), nor to the south over the Southern New England Shelf (Harden et al., 2020). At depth, however, there has been an increase in salinity in the southern portion of the domain, resulting from an onshore shift of the Gulf Stream (Harden et al., 2020), as well as in the Gulf of Maine, resulting from an intrusion of subtropical waters through the Northeast channel (McDowell and Burkholder, 2016).

Projections

As with the historical trends in salinity vis-à-vis temperature, there is greater uncertainty in future changes in surface and subsurface salinity in the domain of interest. Initial simulations (Saba et al., 2016) indicated that surface salinity in the region would increase marginally (~0.5psu), while subsurface salinity would increase substantially (~1psu) in response to the influence of the northward shift of the Gulf Stream and its accompanying saline subtropical waters. However, as with the expected temperature changes, expected changes in surface and subsurface salinity have become less constrained with the inclusion of additional ESM and regional ocean model simulations (Alexander et al., 2020; Shin and Alexander, 2020).

At the surface, expected salinity changes range from +/-0.1 psu (GoM Study, 2019) by 2050 and the difference expands by the end of the century to +/-0.3 psu (Alexander et al., 2020). This difference reflects a difference in the salinity of the offshore water being advected into the region by the Maine Coastal Current circulation. For simulations in which the offshore water becomes more saline, surface intrusions of this water into the Gulf of Maine and over Georges Bank also become more saline, and vice-versa for simulations in which the offshore water becomes fresher. Interestingly, a freshening of the surface coastal waters can occur even in models that experience a weakening and northward shift of the Gulf Stream (Alexander et al., 2020; Shin and Alexander, 2020). In this case, the freshening reflects instead the intensification of the Maine Coastal Current advecting fresher subarctic waters into the region. At depth, most simulations show an increase in salinity of ~0.1 to 0.2 psu by 2050. However, as time progresses, salinity changes become more uncertain and range from ~+/-0.2 by 2100. This is a reflection of the subsurface water masses intruding on the continental shelf at depth both over Georges Bank and into the Gulf of Maine through the Northeast Channel (Alexander et al., 2020) that accompany a northward (or southward) shift of the Gulf Stream.

Open questions and data gaps

As with temperature, the largest data gap regarding our knowledge and understanding of changes in near surface and subsurface salinity of the Marine Environment affecting GBRAG communities is the lack of high-resolution simulations of the waters off our coasts. In contrast to temperature, however, the increasing range in uncertainty is a function of uncertainties in the internal variability of the North Atlantic dynamics and thermodynamics that can overwhelm any climate change signal. Further, there are additional uncertainties in the dynamic response of both large-scale and local currents in this region. Because both the natural and human-induced changes result from changes in the strength and positioning of the Gulf Stream and Labrador currents, as well as the nearshore currents such as the Maine Coastal Current, it is extremely difficult to discern the influences separately, whether in the historic record or in the coming decades. Hence, while substantially more simulations with different global ESMs and different regional ocean models will be needed to better represent the potential range of human-induced salinity changes in our region, it is unclear whether such changes will manifest in the real world given the role of natural variability upon the region.

2.5 CHANGES IN OCEAN CIRCULATION

Review of existing science

As shown in Figure 1, the waters off the coast of the GBRAG region sit at the confluence of two great current systems—the Gulf Stream extension, which brings warm, saline waters north from the subtropics, and the Labrador Current, which brings cold, fresh water south from the subarctic. Both are western boundary currents for their respective ocean gyres, the North Atlantic subtropical gyre centered at about 30 °N and the North Atlantic subpolar gyre centered at about 65 °N. These gyres are predominantly a response to the atmospheric circulations overlying them and, in particular, the positioning and strength of the midlatitude westerlies that prevail over our latitudes. At the same time, they are also influenced by high latitude deep water formation, which drives what is called the Global Thermohaline Circulation.

This slow-moving circulation redistributes water throughout the global oceans, drawing surface water northward from the subtropics via the Gulf Stream, and then after it sinks, expelling it southward along the bottom of the ocean beneath the Labrador Current. Hence the position and strength of both currents are sensitive to changes in the dynamics and thermodynamics of the large-scale atmosphere and ocean (McCarthy et al., 2018). The former dominates on shorter time scales and can cause substantial changes in the current systems, and hence water properties, off the coast of Massachusetts over the course of months to years. The latter, however, dominates on longer time scales and can cause much longer-lived shifts in the two current system. Indeed, it is changes in the latter—termed the Atlantic Multidecadal Oscillation (AMO)—that gave rise to extremely warm marine temperatures in the 1940s to 1950s, followed by extremely cold temperatures in the 1960s to 1970s (Caesar et al., 2018). Currently, the Gulf Stream has begun to noticeably weaken and broaden in response to a slowdown of the AMO (McCarthy et al., 2018), resulting in substantial warming over the southern portion of the domain as the warm subtropical waters diffuse northward into our region, as well as into the Gulf of Maine.

Projections

As noted previously, initial projections using one of the first high resolution ocean models (Saba et al., 2016) suggested a weakening of the Gulf Stream extension, accompanied by a northward shift that effectively displaced the southward flowing Labrador Current. Hence in these simulations, waters off the coast of Massachusetts showed both considerable warming and salinization, both near the surface but more substantially in the subsurface. However, additional simulations for this region indicate that while the weakening of the Gulf Stream seems to be a consistent response to enhanced human-induced warming over the next 100 years, the northward shift is not. In some models, the weakening is accompanied by a southward shift of the Gulf Stream extension by nearly 5 degrees latitude (Alexander et al., 2020; Shin and Alexander, 2020), while in others the northward shift was only marginal (Alexander et al., 2020). One consistent response found in all models, however, was an intensification of the nearshore Maine Coastal Current and its accompanying counterclockwise circulation around the Gulf of Maine. As noted above, it is the intensification of this regional current system that amplifies temperature and salinity changes in the Gulf of Maine and Georges Bank (Shin and Alexander, 2020).

Open questions and data gaps

As with temperature and salinity, the largest data gap regarding our knowledge and understanding of changes in near surface and subsurface currents affecting the marine environments of interest to GBRAG communities is the lack of high resolution simulations of the waters off our coasts. While historical observations may provide some constraints on expected changes in these current systems, much of the historical record has also been a reflection of long-lived, multi-decadal shifts arising from natural variability. Inevitably, similar natural variability will also influence the future state of the current systems, both in the real world and in the model simulations. For similar reasons (but different purposes) the climate modeling community has turned to Large Ensemble (LENS) simulations, in which 40 (or more) simulations are performed using a single numerical model framework. It is likely that to obtain a robust understanding of human-induced changes in the large-scale and nearshore circulations affecting the coastal regions of GBRAG, a similar effort employing regional ocean models will be needed. Unfortunately, these LENS simulations are extremely computationally exhaustive; further the computational resources become even greater when employing the regional ocean models needed to represent the nearshore topography and bathymetry that control the in-flow and out-flow of water around the Massachusetts coastline. For these reasons, it is unlikely that such simulations will be made available in the near future.

3. Domain: Changes in Water Quality

3.1 OVERVIEW

Water quality is defined as the chemical, biological, and physical properties of lakes, rivers, and oceans that make these environments suitable for native species, aesthetic use, and harvesting. Chemical, biological, and physical measures must be integrated in the definition of water quality as they interact in complex ways, determining habitat suitability and environmental health. pH is an example of a chemical measure of water quality, determined by the dissolution of carbon dioxide (CO_2) and the carbonite system. The carbonite system is a series of chemical reactions that hold concentrations of CO_2, bicarbonate (HCO_3), carbonic acid (H_2CO_3) and carbonate (CO_3) in equilibrium in marine waters. The result of shifting these equilibrium reactions in seawater is a lower pH. CO_2 can enter the oceans from atmospheric sources, but it can also be produced from in situ respiration as biological respiration. Excess nutrients lead to plankton blooms, population busts, and low oxygen conditions as decomposers consume the bloom. Physical properties of water such as circulations patterns, tidal flushing, and vertical mixing can exacerbate low pH conditions by restricting water movement and concentrating the impact on marine life. It is only through the combination of chemical, biological, and physical properties can issues of a changing ocean (e.g., pH) be assessed.

We differentiate human-induced impacts on water quality between nutrient enrichment and chemical pollution. The differences are based on the type of impact each pollutant causes. Nutrient enrichment in general causes photosynthetic plankton to rapidly increase in population size. This rapid increase changes the natural mixture of plankton species, leaving higher trophic levels (e.g., fish) without the food resources they require (Keller et al., 1990). The production of toxins in the water column at high concentrations are capable of killing fish or sickening people (Anderson et al., 2002), while rapid decomposition of bloom organisms leads to reductions in available oxygen (Hale et al., 2016). Chemical pollutants are in general defined by their effects on health, reproduction, and growth of marine organisms. Chemical pollutants considered here include petroleum/oil pollution, persistent organic pollutants (e.g., Polychlorinated biphenyls (PCBs) or pesticides), heavy metals, plastics, and pharmaceuticals. Microplastics (smaller than 5mm) generally develop from the breakdown of plastic debris within the marine environment (Álvarez-Muñoz et al., 2016) and have been shown to decrease the health of marine environments, thus plastic pollution is included in discussion of chemical pollution.

Identifying sources, fate, and transport of pollutants and nutrients is the first step in assessing their impact and projecting their potential future effects. In general, sources are defined as point or non-point sources. Point sources are discrete discharge locations of pollutants, such as treated sewage outfalls, industrial wastewater discharges, or pipes that can be individually identified and controlled. Non-point sources are larger-scale and geographically distributed land-use categories or activities that happen in the upgradient watershed. Non-point contributions of pollution eventually make their way to oceans through precipitation flushing pollutants into rivers, contaminants slowly moving through groundwater to eventually discharge into the coastal zone, and leaking infrastructure. The regulatory framework of the Clean Water Act established controls on point sources, while financial investment and effort over the last 40 years have helped address point sources in the GBRAG nearshore area. Non-point sources are currently the focus of regulatory and remediation efforts, but their diffuse occurrence and the lack of an easily identifiable responsible party makes non-point source pollution a more difficult problem to solve.

Once in the marine environment, pollutants are assimilated by marine organisms, settle into sediments, or are flushed out of the coastal zone by the tides. Dissolved inorganic nutrient pollution and chemical pollution are assimilated in the tissues of marine organism. Chemical pollutants tend to bioaccumulate in organisms and become a persistent toxic threat to both human and marine consumers. Chemical pollutants are the dominate sediment accumulators, as their molecular composition prevents degradation and leads to detectable toxic concentrations in marine sediments long after the source of the pollution has been removed. Transport of both types of marine pollutants is controlled by the physical movement of waters within the GBRAG nearshore area. Tides will flush local bays; however, freshwater entering Boston Harbor has a residence time of approximately 10 days (Dettmann, 2001), so contaminants flushed from one part of the harbor can be subsequently advected to other parts of the harbor, increasing the area of impact. Resuspension of sediment contamination by storms and dredging is another transport mechanism for pollutants. Cumulatively, the diversity of pollutant sources, fate, and transport requires a comprehensive regulatory approach.

Regulation 314 CMR 4 sets the Commonwealth of Massachusetts standards for water quality, while the Massachusetts Department of Environmental Protection (MassDEP) and Executive Office of Energy and Environmental Affairs Office of Coastal Zone Management (CZM) oversee protection of coastal habitats. CZM maintains programs for funding coastal pollutant remediation, stormwater controls, non-point source controls, pump-out facilities and marine management, and established no discharge zones (NDZs) to regulate vessel wastes. MassDEP and CZM review applicable federal Environmental Protection Agency National Pollutant Discharge Elimination System (NPDES) permits for discharges from industrial facilities, municipalities, and wastewater treatment to the coastal zone.

3.2 KEY FINDINGS

- Coastal acidification is a response to biological respiration, precipitation and evaporation dynamics, riverine loads of carbon species, long-term variability due to climate change-induced increases of atmospheric CO_2, and circulation patterns delivering low pH water from adjacent sources in the Gulf of Maine (Wang et al., 2020, 2017). The GBRAG nearshore area is likely to see further reductions in pH (Feely et al., 2009). Reductions in eutrophication in coastal ocean environments will help by preventing synergistic drops in pH associated with larger regional patterns that drive down pH.
- The interaction between local and regional patterns of pH is not well constrained in Boston Harbor or Massachusetts Bay because lower pH conditions result from the interaction of multiple stressors. Some harmful algal bloom related species in the Gulf of Maine have been shown to have decreased growth with lower pH (Seto et al., 2019); how changes in the community structure impact harmful algal bloom (HAB) patterns and impacts in GBRAG nearshore environments remains an open question.
- Since 1984, $8.5 billion (USD) have been spent to reduce the nutrient addition to Boston Harbor (MWRA, 2019), and the desired restorative effect managers envisioned has been observed with decreased pelagic primary production (Oviatt et al., 2007), reduced summer phytoplankton biomass (Taylor et al., 2011), reduced benthic metabolism (Tucker et al., 2014), increased seagrass coverage (Taylor et al., 2020) and increased health in Boston Harbor flounder (Moore et al., 2018a).
- The City of Boston has added approximately 70,000 residents over the last decade and projects a similar growth in population over the next decade, which could result in an annual increase of 1.2 billion gallons of additional wastewater treated and discharged to Massachusetts Bay.
- The addition of greenhouse grown cannabis represents a new agricultural nutrient load and has been shown to increase nutrient concentrations in adjacent rivers, increasing concentrations of dissolved phosphorus and nitrate by 28-fold and 8-fold, respectively (Maguire et al., 2018).

The sudden increase of greenhouse-derived nutrients in the rivers delivering water to the nearshore GBRAG area could have severe impacts to phytoplankton biomass and community structure, reversing the gains made by redirecting wastewater discharges offshore.

- Projections are needed to determine how changes in precipitation within GBRAG watersheds will affect nearshore water quality. There is no estimate for future shifts in the nutrient composition of the nearshore environment with increased population.
- Since the 1980s, pollutants stemming from industrial point sources, wastewater discharges, and non-point inputs have been reduced, but legacy contamination from persistent organic pollutants and continued non-point sources of petroleum associated with impervious land use in watersheds persist (Blalock et al., 2020). Within the water column, petroleum products pose the largest contemporary threat.
- While mussel tissue has shown decreases in chemical contamination within Boston Harbor (Hunt and Slone, 2010), blue mussels within the inner portions of Boston Harbor exhibit biomarkers indicating stress from PCBs, likely from the legacy of poor water quality (Blalock et al., 2020). The impact of anthropogenic pharmaceuticals (e.g., caffeine, estrogen) on biota is a relatively new topic, and not well understood, but emerging research suggests a number of potential physiological impacts, including impacts to reproductive success (Ojemaye and Petrik, 2019; Gaw et al., 2014).
- Resuspension of legacy metals (Kalnejais et al., 2010) and PCB contamination due to either storms or dredging will be a consistent issues in the future. Projected increases in river flows could resuspend riverbed sediment and deliver higher chemical pollutant loads from flushed watersheds.
- Because ocean acidification potentially increases the toxicity of metals to certain phytoplankton species (Dong et al., 2020), there needs to be a clear idea of what synergistic effects changing pH and increased metal concentration have on primary producer communities. The longer-term impacts of pharmaceuticals on marine biota is poorly understood and, particularly in densely populated urban waters such as the GBRAG region, warrants the establishment of region-specific long-term monitoring efforts.
- While the majority of Boston Harbor subtidal habitat is naturally unvegetated, eelgrass biomass within Boston Harbor has almost doubled since 1994 (Taylor et al., 2020). Boston's salt marshes have been reduced by 81% since 1777 (Bromberg and Bertness, 2005), but marshes continue to exist either at undeveloped coastal sites or as fringes around the river mouths. These habitats are under threat from pollution from plastics/microplastics and pharmaceuticals.
- Microplastic pollution in Boston Harbor is likely preferentially collected in subtidal eelgrass beds (Huang et al., 2020), reducing the number of species found in bivalve reefs (Green, 2016), and accumulating in mussel tissues (Von Moos et al., 2012). Salt marshes are impacted by microplastics and accelerate microplastic contamination from the degradation of macroplastic accumulated in the marsh (Weinstein et al., 2016).
- Reestablished eelgrass and shellfish beds within Boston Harbor will be impacted by increased plastic fouling and increased concentrations of microplastic debris in marine sediments associated with more people living within the upgradient watershed. The growing population within the Massachusetts Bay watershed will also increase the load of pharmaceuticals and pharmaceutical by-products discharged from treated wastewater. Impact to habitats under the current urban growth paradigm will be an issue of growing importance to GBRAG nearshore restoration and recovery.
- There is no doubt that pharmaceuticals will continue to be a constituent of wastewater. The next planning step should be to determine if there are infrastructure or operational solutions which could establish controls on pharmaceuticals in wastewater. Additionally, there needs to be a systematic quantification of microplastic pollution within Boston Harbor.

3.3 CHANGES IN OCEAN PH LEVELS

Review of existing science

Increasing atmospheric carbon dioxide (CO_2) increases the amount of CO_2 dissolved in the ocean and lowers ocean pH and carbonate ion concentrations. The GBRAG marine environment pH is controlled by atmospheric conditions and by the condition of river water delivered to the nearshore environment, the deposition of acidic compounds, and pH changes during eutrophication associated with high quantities of dissolved nutrients. GBRAG nearshore waters are connected to larger patterns of pH in the Gulf of Maine, and the strength of tidal flushing can determine the process that dominates pH conditions. This ocean acidification decreases the calcium carbonate saturation point and results in degraded marine organisms' shells (Feely et al., 2004).

Projections

Coastal acidification in Massachusetts waters is a response to biological respiration, precipitation and evaporation dynamics, riverine loads of carbon species, long-term variability due to climate change-induced increases of atmospheric CO_2, and circulation patterns delivering low pH water from adjacent sources in the Gulf of Maine (Wang et al., 2020, 2017). The GBRAG nearshore area is likely to see further reductions in pH (Feely et al., 2009). Reductions in eutrophication in coastal ocean environments will help by preventing synergistic drops in pH associated with larger regional patterns that drive down pH.

Oyster and shell fishing may be the first industries to see pH impacts. Shell deterioration, failure of spat settlement, and bivalve mortality rates are projected in response to ocean acidification and shell fisheries should be monitored throughout the GBRAG area for warning signs (Gledhill et al., 2015).

Open questions and data gaps

The interaction between local and regional patterns of pH is not well constrained in Boston Harbor or Massachusetts Bay. This is because lower pH conditions result from the interaction of multiple stressors. Determining which chemical, biological, or physical parameter is most responsible for observations will continue to be a challenge. There is an opportunity to define how larger-scale changes in the Gulf of Maine are manifested in Boston Harbor and Massachusetts Bay. Additionally, even as biological processes contribute to lower pH, lower pH in turn affects biological processes. Some harmful algal bloom related species in the Gulf of Maine have been shown to have decreased growth with lower pH (Seto et al., 2019); how changes in the community structure impact harmful algal bloom (HAB) patterns and other factors in GBRAG nearshore environments remains an open question.

3.4 WATER QUALITY CONDITION, CHANGES IN WATER QUALITY

Review of existing science

Water quality, as defined by the availability of dissolved nutrients, has been well studied within Boston Harbor and Massachusetts Bay. The two main sources of dissolved nutrients within the GBRAG nearshore ocean waters are wastewater effluents and non-point sources in the upgradient river watershed. Forty years ago, Boston Harbor was a eutrophic system impacted by effluent of two wastewater treatment plants (WWTPs) and discharges of semi-solid wastewater sludge (Taylor et al., 2020). Infrastructure consolidation and system upgrades have resulted in the discharge of treated effluent diverted into Massachusetts Bay and terrestrial disposal of dried sludge, cumulatively reducing the nitrogen and phosphorus additions to Boston Harbor by 82% and 94%, respectively (Taylor, 2010).

Since 1984, $8.5 billion (USD) have been spent to reduce the nutrient addition to Boston Harbor (MWRA, 2019). This investment has acheived many restorative effects that managers envisioned, including decreased pelagic primary production (Oviatt et al., 2007), reduced summer phytoplankton biomass

(Taylor et al., 2011), reduced benthic metabolism (Tucker et al., 2014), increased seagrass coverage (Taylor et al., 2020), and increased health in Boston Harbor flounder (Moore et al., 2018a). Phytoplankton species dominance and density in the area of the new sewage outfall appear to be controlled by Gulf of Maine currents and riverine cycles of nutrient export rather than the effluent (Borkman et al., 2016).

Projections

Despite water quality ameliorations from improvements at Boston's WWTP, increased population will lead to increased delivery of wastewater-derived nutrients within nearshore waters. United States Census figures show the City of Boston has added approximately 70,000 residents over the last decade. Projecting a similar growth in population over the next decade, and assuming the average person generates 50 gallons of wastewater per day, an annual increase of 1.2 billion gallons of additional wastewater treated and discharged to Massachusetts Bay should be expected.

Agricultural land use is the dominant non-point source for dissolved nutrients in rivers. Agricultural land use is minimal within the GBRAG area. The land uses in urbanized watersheds of the Mystic, Charles, and Neponset Rivers are not projected to dramatically change. However, the addition of greenhouse grown cannabis does pose a risk as a new agricultural nutrient load. Greenhouse industrial scale plant material is grown through a hydroponic process termed "fertigation," where water and nutrients are co-delivered to the plants. This style of production has been shown to increase nutrient concentrations in adjacent rivers, raising concentrations of dissolved phosphorus and nitrate by 28-fold and 8-fold, respectively (Maguire et al., 2018). The sudden increase of greenhouse-derived nutrients in the rivers delivering water to the nearshore GBRAG area could impact phytoplankton biomass and community structure; however, there is little scientific research on the water quality impacts of cannabis cultivation (Wartenberg et al, 2021).

Open questions and data gaps

Riverine nutrient loads vary annually because of changes in precipitation. Riverine nutrient loads are driven by flow nutrients to the river. Projections are needed to determine how changes in precipitation within GBRAG watersheds will affect water quality nearshore by altering nutrient delivery. Municipal wastewater is a point source of nutrients in the nearshore environment; unlike the rivers, these municipal loads are independent of flow. There is no estimate for future shifts in the nutrient composition of the nearshore environment as human population increases. The Massachusetts Water Resource Authority and the United States Geological Survey maintain nutrient data on Boston Harbor, Massachusetts Bay, and the adjacent rivers. It will be important that these data are continuously updated and examined for early detection of shifting nutrient sources.

3.5 AMOUNT AND TYPE OF POLLUTANTS IN WATER

Review of existing science

Boston Harbor has a history of pollution stemming from industrial point sources, wastewater discharges, and non-point inputs. Since the 1980s, these sources of pollutants have been reduced, however they remain a threat to the health and use of GBRAG nearshore waters. Threats stem from legacy contamination from persistent organic pollutants and continued non-point sources of petroleum associated with impervious land use in watersheds (Blalock et al., 2020). Within the water column, petroleum products pose the largest contemporary threat. Oil spills are a consistent risk in the GBRAGs nearshore areas, where petroleum products are transported by barge, and large ocean vessels remain actively serving Boston's seaports. However, oil more frequently enters from non-point automotive contaminated runoff. This petroleum impact is likely to be focused along Boston Harbor's fringe marshes (Chadhain et al., 2018).

Fringe marshes are important hotspots of biodiversity and biogeochemical nutrient cycling in coastal habitats and their protection is required for a healthy GBRAG coastal environment. Heavy metals and persistant organic pollutants, such as polychlorinated byphenyls (PCBs), were once very common pollutants in Boston Harbor. Lower concentrations of these pollutants has led to drastic reductions in liver disease in winter flounder within Boston Harbor. (Moore et al., 2018b).While mussel tissue has shown decreases in chemical contamination within Boston Harbor (Hunt and Slone, 2010), blue mussels within the inner portions of Boston Harbor exhibit biomarkers indicating stress from PCB, likely from the legacy of poor water quality (Blalock et al., 2020). The impact of anthropogenic pharmaceuticals (e.g., caffeine, estrogen) on biota is a relatively new topic, and not well understood, but emerging research suggests a number of potential physiological impacts, including impacts to reproductive success (Ojemaye and Petrik, 2019; Gaw et al., 2014).

Projections

While the majority of point sources of historic pollutants have been removed, the contamination in sediments persists due to ongoing combined sewer overflow (CSO) point sources. In 2020, approximately 250 million gallons of treated and one million gallons of untreated sewage was discharged via CSOs (MWRA, 2021). While CSO discharges have decreased dramatically from their rate of approximately three billion gallons per year discharge prior to system improvements in 1986, CSOs remain a contemporary pollution source and, along with historic releases, account for the load of petroleum (among other pollutants) within the GBRAG area (Jin et al., 2018). Petroleum pollutants adsorb to organic carbon in sediments and are still detectable throughout the inner harbor (Wang et al., 2001).

The projected increase in Boston's population will likely lead to increased impervious surfaces and urbanization. Nonpoint sources of automotive petroleum pollution are expected to increase in response to changes in precipitation and increased population/automobiles (Blalock et al., 2020) within the GBRAG watersheds. Resuspension of legacy metals (Kalnejais et al., 2010) and PCB contaminations due to either storms or dredging will pose a consistent challenge in the future. Increased storm activity has the potential to resuspend sediments through waves/storm surges, while increased precipitation will lead to greater riverine discharge. Projected increases in river flows could resuspend riverbed sediment and deliver higher chemical pollutant loads from flushed watersheds.

Open questions and data gaps

Further assessments of heavy metal concentrations in urban Boston Harbor would benefit from a collaborative map of current conditions. The spatial distribution of metal contamination is likely highly heterogenous, and a visual representation of existing data could aid both new monitoring efforts and modeling response of hotspots to events that disturb sediments. Because ocean acidification potentially increases the toxicity of metals to certain phytoplankton species (Dong et al., 2020), there needs to be a clear idea of what synergistic effects changing pH and increased metal concentration have on primary producer communities. The longer-term impacts of pharmaceuticals on marine biota is poorly understood and, particularly in densely populated urban waters such as the GBRAG region, warrants the establishment of region-specific long-term monitoring efforts.

3.6 IMPACT OF POLLUTANTS ON HABITATS

Review of existing science

The majority of Boston Harbor subtidal habitat is naturally unvegetated. However, eelgrass biomass within Boston Harbor has almost doubled since 1994 (Taylor et al., 2020). Mussel beds located offshore from Logan Airport and Hull occur within Boston Harbor, while additional mussel reefs and soft sediment mussel beds exist in Massachusetts Bay outside the harbor. Boston's salt marshes have been reduced by

81% since 1777 (Bromberg and Bertness, 2005), however marshes continue to exist either at undeveloped coastal sites or as fringes around the river mouths. These habitats are under threat from pollution from plastics/microplastics and pharmaceuticals. Plastic pollution across Boston Harbor has only been quantified in limited studies (Miller, 2012). Microplastic pollution in Boston Harbor is likely preferentially collected in subtidal eelgrass beds (Huang et al., 2020), reducing the number of species found in bivalve reefs (Green, 2016), and accumulating in mussel tissues (Von Moos et al., 2012). Salt marshes are impacted by microplastics and accelerate microplastic contamination from the degradation of macroplastic accumulated in the marsh (Weinstein et al., 2016). Pharmaceutical pollution and potential impacts to Boston Harbor and Massachusetts Bay have been known for 20 years (Siegener and Chen, 2002, 2000). Pharmaceutical pollution affects the size and diversity of phytoplankton living in the water column (Kline and Pinckney, 2016). Antidepressants are also likely impacting the invertebrate population throughout the GBRAG area (Guler and Ford, 2010).

Projections

Reestablished eelgrass and shellfish beds within Boston Harbor will be impacted by increased plastic fouling and increased concentrations of microplastic debris in marine sediments associated with more people living within the upgradient watershed. The plastic load delivered to the GBRAG nearshore area will be additionally impacted by terrestrial plastic pollution converted to microplastic within protected estuaries. The growing population within the Massachusetts Bay watershed will also increase the load of pharmaceuticals and pharmaceutical by-products discharged from treated wastewater. Impact to habitats under the current urban growth paradigm will be an issue of growing importance to GBRAG nearshore restoration and recovery.

Open questions and data gaps

There is no doubt that pharmaceuticals will continue to be a constituent of wastewater. The next planning step should be to determine if there are infrastructure or operational solutions which could establish controls on pharmaceuticals in wastewater. Additionally, there needs to be a systematic quantification of microplastic pollution within Boston Harbor. In the absence of a data repository, historic results are not available to researchers and data collectors to compare to contemporary observations. This collaborative data collection would guide remediation efforts and establish areas that could be used as "treatment" and "control" in comparing the impact plastic is having on habitats. Typically, the impact on marine organisms due to plastic and pharmaceutical pollution is limited to small sessile organisms. Higher trophic level impacts from pollutants within urban impacted marine habitats should be examined next as these impacts are projected to get worse in the future.

4. Domain: Changes in Coastal Conditions

4.1 OVERVIEW

The shoreline of Massachusetts has been highly altered by artificial structures, far beyond the national average. Suffolk county was highlighted as among the most armored counties in the nation at 94%. Nationally, shoreline armoring is increasing despite the fact that the negative impacts have been well documented for decades. The rate of increase in shoreline armoring is now lower in Massachusetts, due to stricter regulations and lower population increases; however, Massachusetts as well as most of New England, are behind in implementing "living shoreline" management alternatives. Case studies and pilot projects do exist and point the way to future implementation of nature-based coastal solutions. High coastal population density coupled with worsening climate hazard projection mean that future infrastructure investment decision-makers will need to choose between further armoring or expanding nature-based strategies for coastal protection; such decisions will depend on research that elucidates appropriate techniques for New England coastlines as well as societal and political priorities.

4.2 KEY FINDINGS

- Twenty-seven percent of ocean-facing shorelines have been armored (MA CZM, 2013), compared to the national average of 14% (Gittman et al., 2014). Armoring rates in many developed areas of the GBRAG region are much higher including 58% in Boston Harbor, 46% along the North Shore, and 44% along the South Shore. Suffolk County was highlighted as among the most armored counties in the nation at 94%.
- While nature-based approaches to shoreline management, often termed "living shorelines," have become increasingly popular alternatives to shoreline armoring, they have been less common in Massachusetts. However, example projects do exist and provide case studies for planning and considering potentially "greener" trajectories of shoreline change than traditional armoring.
- Nationally, shoreline armoring is projected to double by 2100 (Gittman et al., 2014). Increases in armoring may be less dramatic in MA due to lower population growth estimates and a stricter regulatory environment than some other states; however, permitting and regulatory concerns may also impede the implementation of living shorelines.
- Critical questions for addressing future shoreline change in the Commonwealth and the potential impacts for ecosystems and coastal communities include: What are the biophysical and ecological factors limiting the potential success of natural shorelines in coastal MA? What are the social and regulatory barriers to nature-based and living shorelines in coastal MA?

4.3 CHANGE IN SHORELINES

Review of existing science

The natural shorelines of Massachusetts are diverse and include beaches and dunes (~70%), saltmarshes (23%), and rocky coasts. However, over the past century, much of the shoreline has been altered with artificial structures. According to a 2013 report of MA CZM, 27% of ocean-facing shorelines have been armored (MA CZM, 2013), compared to the national average of 14% (Gittman et al., 2014). Armoring rates in many developed areas of the GBRAG region are much higher including 58% in Boston Harbor, 46% along the North Shore, and 44% along the South Shore. Suffolk County was highlighted as among the most armored counties in the nation at 94%.

Decades of research on shoreline armoring has documented the negative impacts, including lower biodiversity (e.g., Gittman et al., 2015), decreased abundance and resilience of fish communities (Scyphers et al., 2015), and the degradation of other nearby coastal habitats (e.g., Bilkovic and Rogerro, 2008). While nature-based approaches to shoreline management, often termed "living shorelines," have become increasingly popular alternatives to shoreline armoring, they have been less common in Massachusetts. NOAA defines living shorelines as "mostly of native material," such as natural vegetation or other living features, alone or in combination with some type of harder shoreline structure (e.g., rock sills) for added stability. A unifying goal of living shorelines is to maintain or restore connectivity between the land and water to "stabilize the shoreline, reduce erosion, and provide ecosystem services, like valuable habitat, that enhances coastal resilience" (NOAA, n.d).

According to a 2017 report, *Living Shorelines in New England: State of the Practice*, living shorelines remain nascent in Massachusetts and throughout much of New England (Woods Hole Group, 2017). However, example projects do exist and provide case studies for planning and considering potentially "greener" trajectories of shoreline change than traditional armoring. For instance, within the GBRAG region, the planted marsh with a rock sill shoreline at the Encore Casino in Everett is a good example for sheltered, estuarine settings (Figure 2). The project involves marsh planting and a rock sill directly adjacent to a public boardwalk with a retaining wall.

Figure 2
The hybrid living shoreline at the Encore Boston Casino.

The project involves marsh planting and a rock sill directly adjacent to a public boardwalk with a retaining wall.
Photo: S. Scyphers.

Projections

Nationally, shoreline armoring is projected to double by 2100 (Gittman et al., 2014). A key finding of the Gittman and colleagues' study was that storms and population growth were major drivers of armoring. Increases in armoring may be less dramatic in MA due to lower population growth estimates and a stricter regulatory environment than some other states; however, permitting and regulatory concerns may also impede the implementation of living shorelines. Nonetheless, worsening coastal hazards facing dense populations and high-value assets are certain to promote continued investments in coastal protection. With the high densities of communities and economic resources near coastlines, coupled with projections of worsening climate hazards, the big questions related to shoreline change in MA relate to "how," "when," and "at what cost." Expanded shoreline armoring is likely to degrade coastal ecosystems including negative impacts on marshes, seagrasses, and the many species that depend on them. Whether these investments further armoring or expand nature-based strategies for coastal protection will depend on societal and political priorities.

Open questions and data gaps

Moving forward, there are several critical questions that need addressing to project shoreline change in the Commonwealth and the potential impacts for ecosystems and coastal communities. For instance, what are the biophysical and ecological factors limiting the potential success of natural shorelines in coastal MA? The harsher winter climate of New England may limit the types of living shorelines that are feasible, and further ecological studies may be needed to optimize design effectiveness and resilience. Second, what are the social and regulatory barriers to nature-based and living shorelines in coastal MA? The Woods Hole Group (2017) report suggested that the major barriers to living shorelines in the region are the unpredictable and time-consuming permitting processes. Further, very little is known about the attitudes, beliefs, and preferences of shoreline landowners and other decision-makers.

In contrast to expanding living shorelines, another key question is: are there potential policy loopholes that may permit further shoreline armoring under growing concerns for climate change? For instance, how may inland and upland development decisions affect the condition of coastlines as rising seas cause inundation? Collectively answering these questions and others will be essential for projecting the condition of shorelines in the GBRAG region in decades to come.

5. Domain: Changes in Ecological Conditions

5.1 OVERVIEW

Predicting the response of an ecological community to perturbation is an exceptionally challenging process. Not only are biological communities dependent on a complex interplay of physical, chemical, and geological parameters, but they are also heavily dependent on other biological factors, including food availability, predator abundance, inter- and intra-specific competition, and reproductive success. For example, a given species may respond negatively to temperature increases in a lab experiment but respond positively to the same temperature increase in an ecosystem, particularly if the increase has a more severe impact on species that are its predators or direct competitors.

The degree of response also depends on the overall condition of the ecosystem in question. Healthier "idealized" ecological systems are more stable and possess greater capacity for self-repair when perturbed than degraded ecological systems (Karr, 1991). Boston Harbor and Massachusetts Bay are relatively heavily impacted systems. While a substantial amount of effort has been invested in preserving and protecting the ecological structure and function of these water bodies, they remain highly urbanized, and loss and degradation of habitat and water quality remains a pressing management concern (e.g., Oviatt et al., 2007; MWRA, 2019; Taylor et al., 2020). The recent improvements in water quality in the coastal water bodies of the GBRAG area are juxtaposed with increasing pressure on ecological systems resulting from climate change and ocean acidification, and produce a complex web of synergistic effects which makes predicting long-term trends in localized ecological parameters exceedingly difficult, thus creating the distinct possibility that Boston Harbor and its associated water bodies may not follow patterns observed in otherwise similar ecosystems.

Although they are inextricably related, we must do our best to differentiate between natural variation, localized anthropogenic impacts (e.g., nutrient enrichment, land use change, overfishing), and climate change-induced impacts on biota, the last of which is the focus of this report. However, nutrient enrichment and coastal warming in general work synergistically to cause photosynthetic plankton populations to rapidly increase in size, which can, particularly in shallow embayments, lead to seasonal or habitat loss due to hypoxia or anoxia (e.g., Oviatt et al., 2017; Foster and Fulweiler, 2019; Hale, 2016). Furthermore, this rapid increase causes shifts in plankton species assemblages, which can have impacts on higher trophic levels (e.g., fish, shellfish, crabs) by altering food webs (Keller et al., 1990) and promoting harmful algal blooms (Anderson et al., 2002).

Although the inshore waters of Massachusetts Bay and its surrounding embayments are not targeted grounds for many large-scale fisheries, any discussion of ecosystem response to anthropogenic perturbation must necessarily include a discussion of the influence of fisheries, both commercial and recreational, on the ecosystem, and how that may confound any climate signal on the fisheries. New England waters are well surveyed, both by Massachusetts Division of Marine Fisheries, and by NOAA's Northeast Fisheries Science Center, which conducts spring and fall fisheries independent surveys throughout the region. The New England Fisheries Management Council has ten Fisheries management plans which cover 29 species including groundfish, pelagics, and invertebrates.

5.2 KEY FINDINGS

- In general, commercial quotas and catches of major commercial species have been roughly stable over the last two decades, with some species increasing, and others declining (MADMF, 2020). Rapid warming in the Gulf of Maine has negatively impacted species at the lower end of their range, such as Atlantic cod (*Gadus morhua*), yellowtail flounder (*Limanda ferruginea*), and northern shrimp (*Pandalus borealis*), whereas it has promoted the northern expansion of more southerly species such as black seabass (*Centropristes striata*) and blue crab (*Callinectes sapidus*). Increased temperatures have likely decreased the productivity of stocks of key fisheries species that thrive in colder waters such as Atlantic cod (Pershing et al., 2015) and has induced species like the American lobster (*Homarus americanus*) to shift their range northward (Pinsky et al., 2013).
- As the climate continues to shift, it would be reasonable to expect the fish community in Massachusetts to follow the same trend, which would mean decreases in populations for cold water associated species such as winter flounder, American lobster, silver hake, and Atlantic herring, and corresponding increases in warm water associated species such as summer flounder, black seabass, blue crab, scup and butterfish (Howell and Auster, 2012).
- The primary data gaps involve our understanding of how localized conditions will change in response to the complex changes in physical, chemical, and biological parameters resulting from climate change in the greater Gulf of Maine Large Marine Ecosystem (LME). Understanding the impact of recent efforts to restore and protect critical nearshore habitats (saltmarsh, eelgrass, access to riverine habitats for anadromous species, shellfish habitat) on fish population dynamics is a critical and ongoing data gap to predicting future trends in fish abundance and fisheries landings.
- Although sewage discharge has been substantially ameliorated, it remains a significant concern, and current treatment approaches are at or near the limit of technological feasibility. There is tremendous uncertainty associated with riverine and non-point nutrient loads. Projections are needed to estimate how changes in precipitation within GBRAG watersheds will impact coastal water quality.
- Recent modeling efforts suggest substantial potential increases in cyanobacterial blooms in coastal freshwaters of the Northeast, with frequency of blooms potentially forecast to increase by 200 to 300% by 2050 (Chapra et al., 2017).
- Hare et al. (2016) conducted a climate vulnerability assessment of 82 fish and invertebrate species on the Northeast U.S. continental shelf and found that vulnerability is high or very high for half of the species, whereas some will increase their productivity and/or distribution in the Gulf of Maine.
- Marine benthic algal and eelgrass habitats are among the many coastal habitats that are extremely vulnerable to anthropogenic impacts and have been degraded globally (Orth et al., 2006). The Massachusetts Department of Environmental Protection documented a 42% decline in seagrass extent between 1996 and 2006 in Boston Harbor (Leschen et al., 2010); yet, improved water quality, natural recovery, and restoration efforts resulted in a 50% expansion in seagrass habitat throughout the harbor between 2006 and 2016 (Evans et al., 2018) despite some setbacks in the region (Bowen et al., 2019).
- Kelp forests near Boston will likely transition to less desirable ecosystem states. Meanwhile, efforts to improve the water quality of Boston Harbor and the Charles River have likely increased the quality and quantity of seagrass habitat in the coastal waters around Boston (Bowen et al., 2019).
- In many areas, seagrass restoration may be necessary to restore seagrass beds; yet, seagrass restoration has generally been challenged by low success rates (Bayraktarov et al., 2016). Therefore, efforts to investigate how to increase the effectiveness of seagrass restoration methods (e.g., plant source, planting density, etc.) are merited.

5.3 INCREASE/DECLINE IN FISH CATCH

Review of existing science

In general, commercial quotas and catches of major commercial species have been roughly stable over the last two decades, with some species increasing, and others declining (MADMF, 2020). Recent literature suggests that substantial instability in commercial fisheries caused by climate change may be contributing to a reduction of employment availability in the commercial fisheries sector of New England, which although not directly a biological indicator, is tied to biological reference points (Oremus, 2019).

Researchers of nearby estuarine systems have begun to detect changes in the fish community resulting from climate change, with increases in species generally associated with warmer waters, and decreases in species typically associated with cooler waters. Research from Long Island Sound suggests that their fish community is starting to look a lot more like the Chesapeake Bay than the "traditional" New England fish community (Latimer et al., 2013; Wood et al., 2009).

Projections

As the climate continues to shift, it would be reasonable to expect the fish community in Massachusetts to follow the same trend, which would mean decreases in populations for cold water associated species such as winter flounder, American lobster, silver hake, and Atlantic herring, and corresponding increases in warm water associated species such as summer flounder, black seabass, blue crab, scup and butterfish (Howell and Auster, 2012).

In addition to temperature, as discussed in the Water Quality sections, the GBRAG nearshore area is likely to see further reductions in pH (Wang et al.; 2020, Feely et al., 2009) over the medium- to long-term. Although shellfish would likely be the first species to suffer pH impacts (e.g., Gledhill et al., 2015), changes in pH can also impact larval fish development and recruitment. While it is difficult to predict specific responses, this is something that should be carefully monitored moving forward.

Open questions and data gaps

The primary data gaps involve our understanding of how localized conditions will change in response to the complex changes in physical, chemical, and biological parameters resulting from climate change in the greater Gulf of Maine Large Marine Ecosystem (LME). It is not reasonable to expect that Boston Harbor and the surrounding water bodies will respond exactly similar to the larger ecosystem, nor that the response will be identical to other nearby systems.

In particular, the GBRAG region has experienced dramatic reductions in eutrophication due to sewage loading over the last several decades, and still has not reached an alternate "steady state" as a result of these changes. Furthermore, understanding the impact of recent efforts to restore and protect critical nearshore habitats (saltmarsh, eelgrass, access to riverine habitats for anadromous species, shellfish habitat) on fish population dynamics is a critical and ongoing data gap to predicting future trends in fish abundance and fisheries landings. In general, many of the species that are expanding their ranges into the Gulf of Maine, such as blue crab and black seabass, are more dependent on estuaries during critical life history phases. Thus, it will be important to investigate if the role of estuaries in the GBRAG region in providing nursery habitat for fish populations and supporting fisheries expands in the future.

5.4 NUMBER AND EXTENT OF ALGAL BLOOMS

Review of existing science

Algal blooms are driven by several factors. Blooms in general are largely driven by water quality, though the species composition of those blooms (including to some degree the extent and severity of harmful algal blooms) can be impacted by climate variability such as warming and pH. Water quality and dissolved nutrients have been well studied within Boston Harbor and Massachusetts Bay and are addressed in the Water Quality section. In brief, substantial efforts to reduce point source pollution have drastically reduced the nutrient loadings to Boston Harbor (MWRA 2019; Taylor et al., 2020) and led to a suite of positive ecological benefits including reduced plankton blooms (Oviatt et al., 2007; Taylor et al., 2011). Phytoplankton bloom dynamics and species composition and density in the area of the outfall diffusers appear to be driven by Gulf of Maine currents and riverine cycles rather than the effluent (Borkman et al., 2016).

Projections

Although sewage discharge has been substantially ameliorated, it remains a significant concern, and current treatment approaches are at or near the limit of technological feasibility. Increased population over the next decades is likely, and if sustained at present rates (approximately 70,000 per decade) would result in over one billion gallons per year of additional treated sewage discharged into Massachusetts Bay. In contrast, non-point source loading is not likely to change dramatically on the short to mid-term, since most of the coastal population is sewered, and agricultural loadings are relatively stable.

With respect to harmful algal blooms, recent modeling efforts suggest substantial potential increases in cyanobacterial blooms in coastal freshwaters of the Northeast, with frequency of blooms potentially forecast to increase by 200 to 300% by 2050 (Chapra et al., 2017). In marine waters, temperature as well as pH are a concern. Recent research suggests that some harmful algal bloom related species in the Gulf of Maine have been shown to have decreased growth with lower pH (Seto et al., 2019) which may offset potential increases and range expansions from temperature increases (e.g., Hallegraeff, 2010).

Open questions and data gaps

There is tremendous uncertainty associated with riverine and non-point nutrient loads. Projections are needed to estimate how changes in precipitation within GBRAG watersheds will impact coastal water quality. There is no estimate for future shifts in the nutrient composition of the nearshore environment with more people. There is also substantial uncertainty associated with possible confounding parameters, such as pH.

5.5 CHANGES IN POPULATIONS OF MARINE LIFE (FISH, SHELLFISH, BIRDS, MAMMALS)

Review of existing science

As mentioned above, the productivity of fish communities has been relatively stable, but community structure has changed. Rapid warming in the Gulf of Maine has negatively impacted species at the lower end of their range, such as Atlantic cod (*Gadus morhua*), yellowtail flounder (*Limanda ferruginea*), and northern shrimp (*Pandalus borealis*), whereas it has promoted the northern expansion of more southerly species such as black seabass (*Centropristes striata*) and blue crab (*Callinectes sapidus*). Increased temperatures have likely decreased the productivity of stocks of key fisheries species that thrive in colder waters such as Atlantic cod (Pershing et al., 2015) and has induced species like the American lobster (*Homarus americanus*) to shift their range northward (Pinsky et al., 2013). These range shifts create substantial challenges for fisheries management, as reduced populations due to environmental forcing will often result in populations being deemed as overfished, resulting in management actions. However, reductions in fishing effort likely will not reverse population declines due to environmental forcing. Furthermore, fisheries management has found it challenging to keep up with the pace of rapidly expanding species (Pinsky and Fogarty, 2012).

Projections

Efforts to predict marine species range shifts due to climate change in the Gulf of Maine and elsewhere will benefit from incorporating multiple factors in addition to temperature such as seabed characteristics, salinity, and sea surface height (McHenry et al., 2019). Hare et al. (2016) conducted a climate vulnerability assessment of 82 fish and invertebrate species on the Northeast U.S. continental shelf and found that vulnerability is high or very high for half of the species, whereas some will increase their productivity and/or distribution in the Gulf of Maine.

Open questions and data gaps

Building more complex models that incorporate enviromental and habitat parameters will enhance their capacity to predict how climate change will modify the distribution and abundance of economically and ecologically important marine species in the Gulf of Maine (McHenry et al., 2019). Furthermore, investigating the mechanisms that underly how climate change impacts marine communities in the Gulf of Maine will be critical to enhancing our ability to predict how climate change will affect marine community structure and dynamics (Hale et al., 2016).

5.6 CHANGES IN EXTENT OF MARINE ALGAE/EELGRASS

Review of existing science

Marine benthic algal and eelgrass habitats provide a wide range of valuable ecosystem services, such as providing nursery and foraging habitat for juvenile and adult fish and invertebrates, storing carbon, promoting nutrient cycling, stabilizing sediments, and enhancing biodiversity (Thayer et al., 1978, Orth et al., 1984, Rohr et al., 2018). Yet these two habitats are extremely vulnerable to anthropogenic impacts and have been degraded globally (Orth et al., 2006). Seagrass habitat is thought to have covered over 6,000 ha of Boston harbor, whereas more recent estimates suggest that approximately 5% of seagrass habitat remains today (Costello and Kenworthy, 2011; Bowen et al., 2019). More recently, the Massachusetts Department of Environmental Protection documented a 42% decline in seagrass extent between 1996 and 2006 in Boston Harbor (Leschen et al., 2010). Yet improved water quality, natural recovery and restoration efforts resulted in a 50% expansion in seagrass habitat throughout the harbor between 2006 and 2016 (Evans et al., 2018) despite some setbacks in the region (Bowen et al., 2019).

In coastal Massachusetts and throughout New England, both kelp and eelgrass habitats are monitored extensively. For instance, seagrass habitat has been surveyed periodically by the Massachusetts Division of Marine Fisheries over the past 15 years. Seagrass habitat extent from past surveys is available at the Massachusetts Open Resource Information System (MORIS), CZM's online mapping tool (*https://czm-moris-mass-eoeea.hub.arcgis.com/*). Meanwhile, kelp monitoring in coastal New England has been ongoing for almost a decade as part of a global network called KEEN (Kelp Ecosystem Ecology Network), which aims to investigate how global change is impacting kelp forests (*https://www.kelpecosystems.org)*.

Projections

Filbee-Dexter et al. (2020) investigated the effects of extreme climatic events such as marine heatwaves on kelp communities in the eastern U.S. and coastal Norway and found that they were mechanistically linked to broad-scale kelp loss. Given accelerated warming in the Gulf of Maine coupled with the expectation that extreme climatic events will become more frequent over the next couple of decades, kelp forests near Boston will likely transition to less desirable ecosystem states. Meanwhile, efforts to increase the water quality of Boston Harbor and the Charles River have likely increased the quality and quantity of seagrass habitat in the coastal waters around Boston (Bowen et al., 2019).

Open questions and data gaps

A looming area of research in kelp/algal habitats involves investigating how marine heatwaves and global change more generally will impact algal community structure, habitat provisioning for resident and transient fishes and invertebrates, and the delivery of ecosystem services. Seagrass systems have faced numerous anthropogenic stressors from coastal populations, such as sediment and nutrient runoff, physical disturbance, invasive species, disease, commercial fishing practices and aquaculture, overgrazing, and algal blooms (Orth et al., 2006). A better understanding of how these factors independently and interactively affect seagrass populations would aid seagrass conservation efforts. In many areas, seagrass restoration may be necessary to restore seagrass beds, yet, seagrass restoration has generally been challenged by low success rates (Bayraktarov et al., 2016). Therefore, efforts to investigate how to increase the effectiveness of seagrass restoration methods (e.g., plant source, planting density, etc.) are merited.

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Climate Change Impacts on the Marine Environment in the Greater Boston Area

Findings of the Greater Boston Research Advisory Group Report

Climate change has a large impact on the marine environment, yet it has often been overlooked in the development of climate change adaptation strategies. This report looks closer at how climate change is impacting the marine environments of the Greater Boston Area, defined herein as the 101 communities of the Metropolitan Area Planning Council (MAPC) region. The marine environments of interest to MAPC region communities extend from the near shore tidal flats, across shallow waters along the Massachusetts coastline, and out into the deeper waters of the North Atlantic.

Assessing future change in the marine environment is exceptionally challenging because risk factors involve a complex interplay of not just physical processes and parameters, but also chemical, geological, and biological ones as well. This study assessed the following risk factors: changes in physical environment, water quality, coastal conditions, and ecological conditions.

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