Climate Change and Variability

A White Paper to Inform the Mid-Atlantic Fishery Management Council on the Impact of Climate Change on Fishery Science and Management

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Introduction

The Fourth International Panel on Climate Change (IPCC) Assessment Report provided compelling evidence that the Earth's physical and biological systems on all continents and in most oceans are being affected by recent climate changes, particularly with respect to regional temperature increases. More recently, the Fifth IPCC Report (http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_SPMcorr1.pdf) provided the following assessment of climate change over the last several decades:

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. Human influence on the climate system is clear; it has been detected in warming of the atmosphere and ocean, in changes in the global water cycle, in reductions of snow and ice, in global mean sea level rise, and in changes in some climate extremes.

The need to understand climate change and the associated impacts on the ocean environment has emerged as perhaps the most important challenge facing contemporary marine fishery science and management. Understanding the effects of multi-decadal climate variability are similarly important. There are numerous natural climate signals with multi-year periods that contribute to trends in the environment: the North Atlantic Oscillation, the Atlantic Multidecadal Oscillation and the El Nino Southern Oscillation. To address these issues, the Mid-Atlantic Fishery Management Council (Council) is currently developing an Ecosystem Approach to Fisheries Management (EAFM) Guidance Document which is intended to inform Council policy with respect to the incorporation of ecosystem considerations into its current management programs. Foremost amongst these considerations are the impacts of climate change and climate variability on the ocean environment and the associated impacts on fish populations and fisheries they support within the Northeast U.S. Continental Shelf Large Marine Ecosystem (NE LME).

The Council was recently engaged in a Visioning Project to shape the future course of marine fisheries management in the Mid-Atlantic based on constituent input (MAFMC 2014c). That process revealed an overwhelming desire on the part of constituents across all fishery sectors to integrate ecosystem considerations, including environmental influences on fish stocks due to climate change and variability, into fishery stock assessments and Council management policy. In response, the Council hosted a series of workshops in 2014 to evaluate the current state of climate science, the expected range of climate impacts on fish stock distribution and productivity, and to evaluate the impacts of these changes on fisheries management given the existing governance structure along the Atlantic Coast.

The first workshop, Climate Science and Fisheries (MAFMC 2014a) examined the current state of climate science and our understanding of the impacts related to climate change and variability on marine fish populations and the fisheries they support. The overall goal was to examine where/when climate considerations need to be addressed in the assessment-management continuum and how these considerations should be integrated into the existing fishery management process. Following the Climate Science Workshop, the Council hosted a 3-day workshop that convened more than 70 fishery managers, scientists, Atlantic coast policy makers, and stakeholders to examine the management and governance implications of climate change and variability for Atlantic Coast marine fisheries (MAFMC 2014b). Atlantic Coast fishery management partners participate in managing 49 different federal and interstate fishery management plans, many of which include multiple species and stocks. This complex system of authority, responsibility, information, and interests involves a corresponding network of interactions between management partners. This governance complexity is overlaid with management complexity, which derives from the wide range of biological, ecological, social, and economic management objectives identified for Atlantic Coast fisheries, and the array of tools used to support them. By changing the distribution and abundance of fish stocks, climate change and variability is expected to introduce even greater complexity and uncertainty into an already complicated management process.

The purpose of this climate white paper is to frame our understanding of the impacts of climate change and variability on the marine resources under the management purview of the Council, including implications for marine ecosystems, fish stocks, fishery management, and the communities and economies that depend on them. The document will inform the development of future Council management actions that seek to incorporate ecosystem considerations into its existing management programs. Having a reasonable understanding of the future state of the ecosystems in the Mid-Atlantic as they respond to climate change and variability is a fundamental prerequisite to the development of management policies that allow for the achievement of the Council's vision for the future of fisheries which exist within those ecosystems.

Climate Change and Variability in Northeast US Shelf Ecosystems

Description of the Oceanography of the Northeast U.S. Shelf Ecosystem

Oceanography is central to Ecosystem-Approach Fisheries Management and climate change science (Cury et al. 2008). Oceanography defines the physical and biological framework of a marine ecosystem. Interactions of higher-trophic levels then define ecosystem dynamics and fisheries. Climate change and variability affect the physical aspects of an ecosystem that then affect the biologicals aspects, directly and indirectly. For example, direct effects can include

Definitions: Climate Change and Climate Variability (source: Climate.gov)

Climate Change is a significant and persistent change in an area's average climate conditions or their extremes. Climate change represents a "shifting baseline."

Climate Variability is different from climate change. Seasonal variability and multi-year cycles constituent natural components of the climate system. For example, the Atlantic Multi-decadal Oscillation represents cold and warm periods in the North Atlantic Ocean with an approximate periodicity of 50-90 years. Other natural components of variability include interannual variability, the North Atlantic Oscillation and the El Nino Southern Oscillation.

The Mid-Atlantic region is experiencing both climate change and climate variability.

physiological effects of temperature (Hare and Able 2007) and indirect effects can include changes in species interactions resulting from changing distributions (Friedland et al. 2013).

The Northeast U.S Shelf extends from Cape Hatteras, North Carolina to the western Scotian Shelf (Figure 1). The Ecosystem is influenced by two major ocean currents: the Gulf Stream and the Labrador Coastal Current System (Loder et al. 1998). The Gulf Stream forms the western boundary of the North Atlantic Gyre and flows northeastward along the east coast of North America. The current carries warm and salty water northwards. From the Florida Straits to Cape Hatteras, the Gulf Stream flows along the shelf-edge and plays a direct role in shelf circulation. North of Cape Hatteras, the Gulf Stream separates from the shelf and flows into the Atlantic Ocean. The Gulf Stream indirectly influences Northeast U.S. Shelf circulation through meanders and eddies, and occasionally the Gulf Stream itself interacts directly with the shelf (Gawarkiewicz et al. 2014). Meanders and the Gulf Stream itself are more likely to interact with the southern Mid-Atlantic Bight shelf than the more northern portions of the ecosystem (Hare et al. 2001). The oceanic area between the Northeast U.S. Shelf and the Gulf Stream is known as the Slope Sea. Shifts in the position of the Gulf Stream off the Northeast U.S. Shelf are a leading indicator of conditions on the shelf (EcoAp 2012) and indirectly related to the distribution of some commercially important fish species (Nye et al. 2011) as well as changes in plankton community composition (Saba et al. 2015). The mechanisms affecting these relationships remain unresolved.

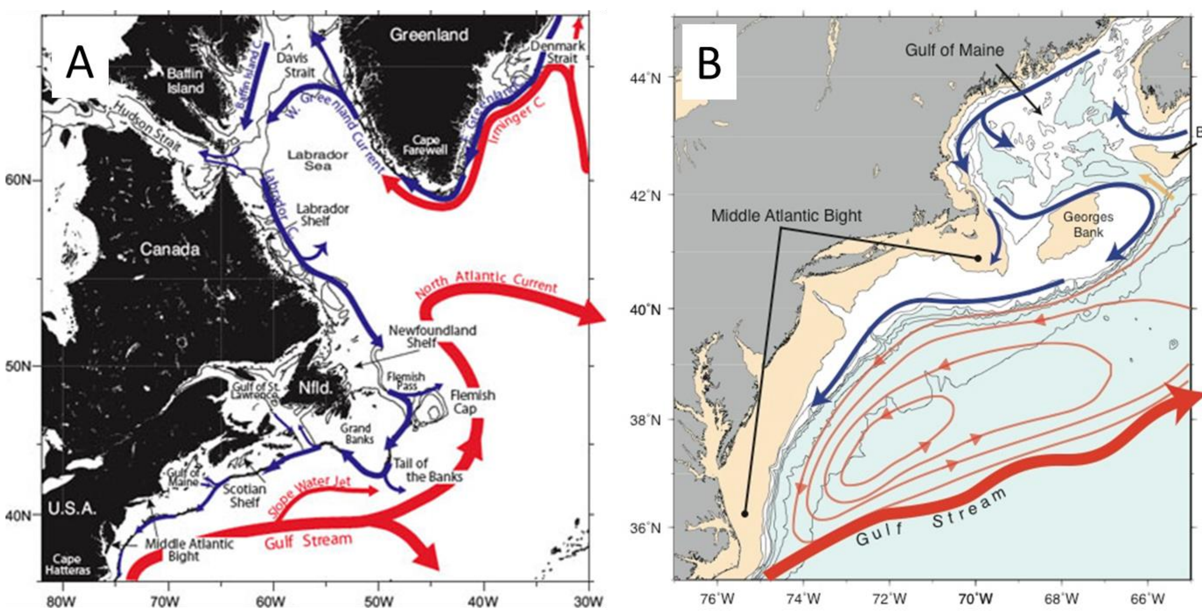

Figure 1. A. The general circulation of the Western North Atlantic showing the two dominant current systems: the Gulf Stream and the Labrador Current. B. The general circulation of the Northeast U.S. Shelf Ecosystem, which extends from Cape Hatteras North Carolina to the western Nova Scotia.

The Labrador Coastal Current System originates along the western boundary of the Labrador Sea and is part of the larger basin-wide gyre circulation in the northern North Atlantic (Loder et al.

1998) (see Figure 1). The current system carries a combination of cold and fresh Arctic-origin water, accumulated coastal discharge, and ice melt along the continental margin. A shallow portion of the current system enters the Northeast U.S. Shelf from the Scotian Shelf and a deeper portion of the current system enters the Northeast Channel. The coastal current loops counter-clockwise in the Gulf of Maine, clock-wise around Georges Bank, and then southwestward along the Mid-Atlantic Bight. A shelf-slope jet forms at the boundary between the cooler-fresher shelf waters and the saltier-warmer slope water. Shelf water also leaves the shelf along the shelf edge and the remaining water turns northeastward at Cape Hatteras in association with the Gulf Stream. The dynamics of this current system have been linked to numerous ecosystem processes (Ji et al. 2007, Townsend et al. 2010), but again the mechanisms affecting these relationships remain largely unresolved.

Freshwater input from rivers and estuaries also contribute to the dynamics of the Northeast U.S. Shelf. Coastal circulation is influenced through the influx of less dense water on the continental shelves, which generally flow southwest along the coast. Most freshwater enters marine systems through rivers, rather than direct precipitation or runoff. River flow is tightly correlated in the Gulf of Maine and Southern New England regions, resulting in coherent freshwater forcing in the northern portion of the region. Time series of annual river flow into the Mid-Atlantic region has a slightly different pattern than for the Gulf of Maine and southern New England. In general, stream flow into all three regions has increased over the past decade, with the largest increases occurring in the Mid-Atlantic and Gulf of Maine regions (EcoAp 2012). Freshwater run-off transports pollutants and nutrients to the continental shelf, which can affect coastal ecosystems. Nutrient over-enrichment – termed eutrophication – is a major problem in many coastal systems and has been linked to increased algal biomass (including harmful algae species), hypoxia/anoxia, and increased water turbidity (Kemp et al. 2005). Pollutants are much less studied but are potentially important to the dynamics of living marine resources (Mills and Chichester 2005).

Winds are an important pressure on shelf ecosystems. Wind stress (the force of the wind on the surface of the ocean) acts to vertically mix the water column and drive horizontal currents. The greater the wind stress, the more vertical mixing and the more force for driving horizontal currents. In the Northeast U.S. Shelf Ecosystem, winds are responsible for breaking down seasonal stratification in the fall and for causing reversals in the general southwestward surface currents during summer. Winds are on average out of the northwest (blowing eastward and southward). Obviously, there is weather system and seasonal variability. There also is inter-annual variability in these average winds. However, there is also evidence of longer-term changes in the strength and location of the jet stream (Archer and Caldeira 2008) and the extreme warmth of 2012 in the region has been linked to a persistent northward displacement of the jet stream (Chen et al. 2014).

Tides are also an important part of the ecosystem's oceanography. Tides throughout the Northeast U.S. Shelf are mixed semidiurnal; two high and two low tides per day, with one high tide higher than the other and one low tide lower than the other (Moody et al. 1984). There are five important tidal constituents in the region: M_2 (principal lunar semidiurnal), N_2 (larger lunar elliptic semidiurnal), S_2 (principal solar semidiurnal), K_1 (lunar diurnal), and O_1 (lunar diurnal). Tidal amplitude increases from the shelf break toward shore and into shallower water. The Gulf of Maine-Bay of Fundy region has higher amplitude because the internal resonance of the region is ~13 hours, which is close to the frequency of the M_2, N_2, and S_2 tides. Stratification significantly influences the vertical structure of the tidal currents (Chen et al. 2011); thus there are important interactions between the water column, bathymetry, and tides on the Northeast U.S. Shelf.

Recent changes in the physical oceanography of NE Shelf Ecosystem

The Northeast U.S. Shelf Ecosystem is changing. These changes results from natural long-term climate variability and anthropogenically forced climate change. The North Atlantic Oscillation and Atlantic Multidecadal Oscillation are two dominant climate variability signals in the Northeast U.S. Shelf. The North Atlantic Oscillation describes a pattern of pressure differences across the basin affected by fluctuations in the strength and position of Icelandic low and the Azores high. The NAO is linked to variability in winter severity in the Northeast and the strength and direction of westerly winds and storm tracks across the North Atlantic. The Atlantic Multidecadal Oscillation describes a pattern of warming and cooling across the North Atlantic with a period of approximately 50-90 years. The regularity of the AMO is questioned because the observational record extends back only about 150 years. Both the NAO and AMO have been linked to numerous biological changes in the ecosystem. The NAO has been linked to patterns in oceanographic variables (Greene and Pershing 2003, Greene et al. 2003) and fish recruitment (Brodziak and O'Brien, 2005, Sullivan et al. 2005, Hare and Able 2007). Recent analyses indicate, however, that the relationship between the NAO and some biological and oceanographic variables may be breaking down (Hare and Kane 2012). Wood and Austin (2009) described a pattern of antagonistic recruitment between Chesapeake Bay anadromous and shelf-spawning species and linked this to climate variability in the region. This work suggests that there are other important patterns of climate variability, in addition to the NAO and AMO that need to be investigated.

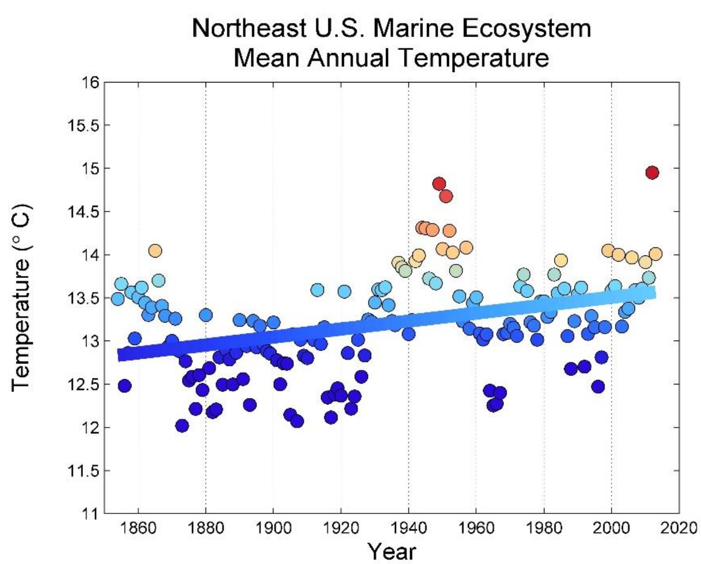

Figure 2. Annual temperature of the Northeast U.S. Shelf Ecosystem based on the Extended Reconstructed Sea Surface Temperature Analysis (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html)

Climate change is also an important factor in the Northeast U.S. Shelf Ecosystem. Ocean temperatures have increased by 1.3°C since 1854; this is a climate change signal (Fig 2). Ocean temperatures also clearly show the AMO signal with high temperatures in the late-1940's and early 2010's. This temperature record demonstrates that the conditions we experience are a combination of climate change and climate variability. Further, that climate variability is composed of multiple components including the multidecadal AMO and interannual variability. The climate change signal is also observed in ocean acidification (Bates and Peters, 2007). A comparison of carbonate chemistry parameters from the late 1970's and early 1980's to the 2000's indicates that pH has decreased at a rate comparable with other global observations. As CO_2 increases in the atmosphere, it increases in the ocean, and as a weak acid, it leads to a decrease in pH. There is also important seasonal and regional variability in carbonate parameters in the Northeast U.S. Shelf, but there is currently not enough data to describe interannual or longer-term variability. Sea level is also rising as a result of warming oceans, melting ice on land, and regional subsidence. The Mid-Atlantic is a region of increased sea-level rise with rates ~ 3–4 times higher than the global average (Sallenger et al. 2012). Rates of sea live rise have also accelerated in recent decades (Sallenger et al. 2012). The causes of the regional increase in sea level rise is an area of active debate (Ezer et al. 2013, Rossby et al. 2014). There are likely other climate change signals (e.g., precipitation), but these are more difficult to separate from climate variability.

Climate Modeling and the Northeast U.S. Shelf Ecosystem

General circulation models (or climate models) are constructed to understand and predict the dynamics of the earth's climate (Stock et al. 2011). Climate is a statistical description of relevant quantities (e.g., air and sea surface temperature, precipitation, wind) in terms of mean and variability over a period in time ranging from months to thousands or millions of years (Baede, 2007). Climate models divide the earth into grids both horizontally across the surface and vertically into the atmosphere and into the ocean. The grid size for most current global climate models in >1^{o} latitude, so many of the mesoscale and smaller processes are not modeled dynamically. The coastline, terrain, and bathymetry also are course. Thus, these models do not capture the regional scale oceanography, but do capture the larger scale climate forcing on the region. Additionally, these models are not synced with the natural climate variability and have limited utility in near-term prediction (i.e., they have NAO like dynamics, but the model NAO is not necessarily in phase with the real NAO). Generally, the output of these models is averaged over several decades to "average over" the natural variability. Also, there is a strong culture of ensemble modeling in climate science where multiple model runs and multiple models are used to make inferences regarding the future climate. There are current efforts to improve the decadal predictability of climate models (Yang et al. 2012) and to create high-resolution climate models (Delworth et al. 2012).

Climate models project changes in the Northeast U.S. Shelf Ecosystem. Increases in temperatures, decreases in salinity, increases in precipitation, decreases in pH, and sea level rise are projected. The largest source of uncertainty stems from the greenhouse gas emission scenario used. Under a business as usual scenario, predicted changes are large [1]. Air temperatures are projected to increase 1-2^{o}C comparing the period 1956-2005 and 2006-2055. Ocean temperatures are projected to increase 1-1.5^{o}C. Salinity is projected to decrease ~0.1 in the Gulf of Maine and increase 0.1 in the Mid-Atlantic Bight. Precipitation is projected to increase ~50 mm yr^{-1} with concomitant increases in streamflow. Ocean acidification is projected to continue with additional

[1] http://www.esrl.noaa.gov/psd/ipcc/ocn/

decreases of 0.1 pH units. Sea level increases of 1 to 2 feet are projected for the Mid-Atlantic by 2100 (Yin et al. 2013), but there is a lot of variability in this estimates owing to the uncertainty of ice melt (Paris et al. 2012). If reductions in greenhouse gas emissions are achieved, these projected changes are less. Improvements in climate models will lead to improved climate projections, but the Northeast U.S. Shelf and the Mid-Atlantic Bight have seen changes in climate over the past 50 years and these changes will likely continue in the near term.

There are three important caveats in terms of climate modeling in the Northeast U.S. Shelf. An important source of error in current climate models is the Gulf Stream path, which is generally too far north. This causes many models to be too warm in the region. This does not affect the relative increases in temperature and salinity described above, but will influence ocean dynamics in the climate models, the effect of which is unclear. Increased resolution of climate models and coupling with a regional ocean model will improve the Gulf Stream separation point and should be a priority for the region. The AMO signal is dominant in the system (Figure 2; large scale oscillations with peaks in the 1860's, 1950's, and 2010's). The duration of the current high-state of the AMO is uncertain but will be important to conditions on the Northeast U.S. Shelf over the next 10 years. Improving decadal predictability should improve projections of the AMO. Finally, the NAO is important to regional ecosystem dynamics but a recent change in the relationships between the NAO and regional physical and biological factors remains unexplained (Hare and Kane 2012). Addressing these issues and others will improve the understanding of the effect of climate variability and change on the Northeast U.S. Shelf Ecosystem and its living marine resources.

Effects of Climate Change on Species Distributions, Production, Habitat, and Assemblages within Northeast U.S. Shelf Ecosystem

There are multiple potential biological responses to the pressures of climate variability and climate change. In general, the anticipated pressures that could affect fisheries in the Northwest Atlantic basin include: warmer water, changing volume of thermal habitat, shifting local hydrography (e.g., fronts, local winds and currents), changing large scale hydrography (e.g., altered boundary currents), changing water chemistry (fresher, more acidic, lower oxygen), changing primary production and other bottom up forcing, changes in species composition including invasives, or natives from other regions, and changes to habitat including loss of deep water coral and of coastal wetlands (Doney et al., 2012; Drinkwater et al., 2009; NCIA, 2006; Frumhoff et al., 2007; Harris and Tyrrell, 2001; Scavia et al., 2002). At the community or population scale, the basic biological attributes regulating population fluctuations (and therefore of interest to fishery management) include productivity, physiology, process timing or phenology, ecological context (primarily predator-prey and competitive interactions with other species), and spatial distribution (both range and center) (Nye et al., 2009; Rijnsdorp et al., 2009; Rose, 2005; Hare et al., 2010; Fogarty et al., 2008). Changes in species range dynamics and life history phenology in response to climate change are occurring more rapidly in the ocean than on land because of the tight coupling of organisms to the ocean fluid which is in turn tightly coupled to the atmosphere and climate. Ocean circulation, water mass properties, and water mass dynamics are controlled by water and heat exchange and the transfer of momentum by winds along the air-sea interface. These ocean-atmosphere interactions are particularly important in controlling habitat dynamics in the mid-Atlantic region where planetary forcing in the form of tides is relatively weak. Dramatic habitat changes are also expected from sea-level rise.

Numerous studies have demonstrated long-term changes in the distribution and productivity of fish and shellfish resources on the Northeast U.S. Shelf. Changes in distribution have been documented in a large number of populations. Weinberg (2005) found changes in Atlantic Surfclam distributions and linked these changes to increased mortality inshore owing to increasing temperatures. In this case the shift in distribution was caused by differences in productivity over space. Nye et al. (2009) found that about two-thirds of the species studies had shifted distribution, most, but not all shifting northeastward on the shelf. Species in the Gulf of Maine were much less likely to show shifts in distribution compared to the Mid-Atlantic Bight. One possible explanation is the complex bathymetry of the Gulf of Maine compared to the relatively simple bathymetry of the Mid-Atlantic. Pinsky et al. (2010) also documented changes in distribution and linked many of these changes to long-term changes in temperature (see text box). These long-term distribution changes across multiple species are also causing shifts in community composition on the Northeast U.S. Shelf (Lucey and Nye 2010). These changes in distribution have important implications for spatial allocations and stock identification (Link et al. 2010). Animations of the distribution of a number of species from the 1970's to the present are available[2].

Fewer studies have examined changes in stock productivity. A recent Southern New England Yellowtail Flounder assessment (NEFSC 2012) indicated that a change in the environment may have resulted in a decrease in productivity. Based on this hypothesis, the reference points for the stock were changed. Bell et al. (2014b) examined Southern New England Winter Flounder and Summer Flounder. They concluded that Winter Flounder productivity had decreased and this decrease was related to increasing temperature. Productivity of Summer Flounder showed no change. These analyses indicate that changes in productivity do occur but that there are species specific differences. A recent meta-analysis (Szuwalski et al. 2014) suggests that changes in productivity are widespread but also that different species show different patterns of productivity change. Twenty-five percent of the stocks examined on the Northeast U.S. Shelf showed patterns of reduced productivity, whereas thirty-three percent exhibited increased productivity. The remainder show no change or variable productivity. The cause of changes in productivity was not examined.

Changes in distribution are caused by at least three factors: fishing, climate variability, and climate change. Separating the relative importance of these different factors in causing changes in fish and shellfish dynamics is difficult. In a recent study, Bell et al. (2014b) analyzed distribution of four species relative to length-structure, ocean temperatures, and population size. The distribution of Summer Flounder was related to length-structure of the population. Larger fish are found further north, and as the population rebuilt and larger fish became more common, the distribution shifted northward. In this example, much of the change in distribution could be linked to the rebuilding of the population, which resulted from decreasing fishing effort. The

[2] http://www.nefsc.noaa.gov/epd/ocean/MainPage/fish/fishmovies.html

distributions of Scup and Black Sea Bass are related to shelf temperature with the populations further north in warmer years. Interestingly, the link between distribution and climate was only observed in the spring and not in the fall, indicating that there are important seasonal drivers as well; these need to be explored in more detail.

There will also likely be changes in species interactions. These physical changes in climate are accompanied by a host of biological changes. At a fundamental level, phytoplankton and zooplankton species composition show coherent decadal scale variability and changes in these lower trophic levels have been linked to changes in fish populations (Mountain and Kane 2009, Friedland et al 2008, Friedland et al. 2013). Changes in forage fish abundance have also been identified as causing changes in the distribution of fish species and the distribution of the fishery (Richardson et al. 2014). The role of climate-forced changes in predator-prey dynamics needs to be investigated, but large-scale changes in species compositions suggests large-scale changes in predator-prey dynamics.

Climate change and variability will also impact protected species and thereby change the interactions between protected species and fisheries. First, owing to climate change, additional species may be threatened with extinction and be listed under the Endangered Species Act. When Atlantic Sturgeon was listed in 2012, there were a number of implications for fisheries in the Mid-Atlantic region (Apostle et al. 2013). If other species are listed (e.g., river herring), a similar range of issues will be encountered. Climate change and variability will also change the distribution of protected species and thereby affect the overlap between fishing activities and protected species. A specific example is as the Northeast U.S. Shelf warms, sea turtle species may move northwards and spend longer in the ecosystem, thereby increasing the probability of encounter (Braun-McNeill et al. 2008). Similarly, recent changes in North Atlantic Right Whale distribution and migrations have been noted. As there are changes in distribution

Climate change and variability will impact the habitats of fish and shellfish in the Mid-Atlantic region. Habitat is defined as an ecological or environmental area that is used by a species. Essential Fish Habitat (EFH) is a statutory definition defined in the MSFCMA as "those waters and substrate necessary to fish [and shellfish] for spawning, breeding, feeding or growth to maturity”. Owing to statutory requirements, there are a number of regulatory and management issues related to EFH and the broad definition of EFH encompasses most, if not all areas in a the Northeast U.S. Shelf Ecosystem ranging from offshore pelagic areas to nearshore wetlands to streams and rivers .

Climate change and climate variability will cause changes in physical attributes of habitat. Because most marine organism are water breathing ectotherms with tissue densities that are close to seawater, the properties of and processes occurring in seawater are critical habitat dimensions. Metabolic rates for most marine organisms are regulated by seawater temperature, limited by the oxygen concentrations of seawater and controlled by concentrations of prey. Horizontal and vertical currents “thicken the soup” by concentrating prey and other organic materials, and redistribute re-mineralized nutrients into well-lit surface waters where they are fixed by phytoplankton, and algae to support food webs. Furthermore currents have strong effects on the energetics of marine organism whose movements are constrained by drag rather than by gravity.

Thus dynamic properties of the ocean fluid are critical habitat features that have strong effects on metabolic rates that underlie most performance rates determining the growth rates of populations. Ocean acidification – increases in dissolved CO2 and decreases in pH - will continue and will effect physiology, calcification, olfaction and other biological components of individuals. Increases in temperature will also change the distribution of snow accumulation and the timing of snow melt thus changing the timing and magnitude of streamflow. Increases in precipitation will also lead to increases in streamflow and freshwater discharge into coastal systems. These changes in physical habitat will have directed (e.g., physiological) and indirect (e.g., survey availability) impacts to managed species.

Climate change and variability will also cause changes in biological habitats. Increases in dissolved CO2 will increase productivity of macroalgae and sea grasses (Koch et al. 2013) potentially increasing their capacity to provide shelter for managed species and for the prey of managed species. However, increases in turbidity owing to increases in streamflow may decrease macroalgal production (Moore et al. 1997). Increased temperatures in the Chesapeake Bay have already contributed to significant die-offs of eelgrass (Moore and Jarvis 2008), which provides important nursery habitat for juvenile fish, including summer flounder. Ocean acidification may also impact deepwater coral, but information is very limited (Movilla et al. 2014). Sea-level rise will put pressure on nearshore habitats, especially where coastal hardening has occurred and natural marsh migration is restricted (Kirwan and Megonogal 2013). For example, Rhode Island has lost more than half of its saltmarshes in the last 200 years; a 3 foot rise in sea level results in the loss of a significant percentage of remaining marsh area[3]. From 1998-2004, the Atlantic coast lost 7,360 acres of estuarine saltmarsh, primarily along shorelines near Delaware Bay due to erosion and/or inundation related to increases in sea level (Dahl and Stedman, 2013). Possible increase in storm intensity and frequency, will also impact coastal habitats (Villarini and Vecchi 2012).

Effects of Climate Change and Variability on Fisheries Stock Assessments

The primary effects of climate on fisheries population dynamics parameters and stock assessments are changes to population vital rates and consequent changes in biological reference points. All of the vital rates in a stock assessment model are likely to be vulnerable to climate change, including recruitment, natural mortality, somatic growth dynamics, and maturity. Changes in somatic growth will result in changes to the age-length key, changes in the length-weight relationship and, therefore, changes to the relationship between abundance and biomass. If the average size is changing, the relationship between abundance-at-age and biomass changes as well. Changes to the fecundity-at-age relationship impact recruitment. There are few, if any, vital rates or population processes that can safely be considered invulnerable to climate change.

Climate change is also likely to affect the observation model component of stock assessments through changes in how we interpret both fishery dependent and independent data. Any impact of climate change that alters catchability can affect the way data are interpreted in the stock

[3] http://seagrant.gso.uri.edu/state-adopts-slamm-maps-wetland-restoration-adaptation/

assessment model. For example, shifting spatial distributions, which are already well underway for many species in the mid-Atlantic region (Nye et al. 2009, Pinsky et al. 2013), may alter the proportion of the stock that is vulnerable to the survey or to the fishery. As a stock shifts into the survey area, we would expect to see higher survey CPUE. If the spatial dynamics of the stock are not understood and incorporated into the assessment, this increase in CPUE would be mistakenly interpreted as an increase in overall stock size (see Link et al. 2012). Thus climate change has the potential to further exacerbate the problem of changing survey catchability. Likewise, shifting spatial distributions of target species can alter catchability within commercial and recreational fisheries. If the distribution of the stock has shifted such that a greater proportion is vulnerable to the fishery, then the same management measures (e.g., seasons and bag/trip limits) that were sufficient to achieve a target catch in the past may now result in unexpected overages.

Stock assessment models that treat vital rates and biological reference points as stationary (i.e., variable, but with a constant mean through time) will be slow to adjust to the impacts of climate change. If we consider a simple step change in vital rates to a new “productivity regime” (Vert Pre et al. 2013), then as the number of years in the new regime increases, the assessment model estimates of stationary vital rates will eventually come to resemble more and more closely those of the new regime. However if the productivity regime changes frequently or continuously, then an assessment model with stationary vital rates will always be chasing a moving target. In this case, biological reference points may always be outdated as they are based on a weighted average of past vital rates. Stock assessment models that explicitly incorporate environmental drivers (see section 4) have the potential to adapt much more quickly. It is also important to note that the biological reference points currently used by the Mid-Atlantic Fishery Management Council are F_{msy} proxies rather than model derived estimates of F_{msy}. Model updates would not affect the proxy reference points, *per se*, since they are determined external to the model. The debate in the fishery science community about whether the use of proxies is a better approach than using the direct estimates of MSY reference points is currently unsettled. However, there is value in direct estimation of MSY reference points, in part because if you have a stock assessment model that incorporates climate, then those reference points could potentially update automatically.

Effects of Climate Change and Climate Variability on Social and Economic Assessments

Assessing the impacts of climate change on recreational and commercial fishermen and their communities consists of assessing the current composition of fisheries, and understanding the likely social, cultural, and economic dynamics accompanying the biological and ecological changes expected to occur. There is a great deal of information available in the assessment of the current state of affairs. Historical and current data exist on recreational and commercial landings by port along with community profiles (Clay et al. 2010). These data have been augmented by demographic and community level data to develop community level vulnerability and resilience assessments (Jepson and Colburn 2013; Colburn and Jepson 2012). These assessments help us to understand not only the changing distribution of landings, but also the relative capacity of fishing communities to adapt to a changing environment. As an example of this work, Figure 3 presents a map of exposure, an important consideration when categorizing vulnerability, indicating the relative dependence of communities within the Northeastern Shelf system on recreational fishing. This vulnerability work is being expanded to consider communities' full exposure to the impacts of climate change, including rising oceans, species vulnerability, and other non-fishery impacts.

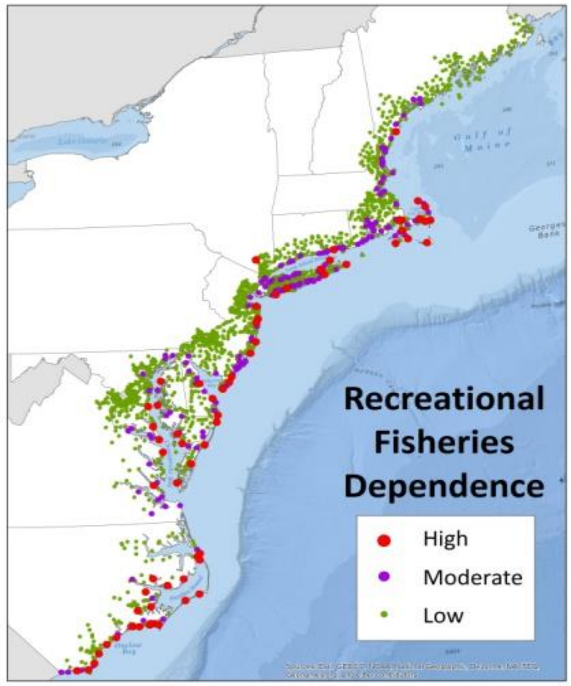

Figure 3Community dependence on recreational fishing across the Northeastern Shelf system

A great deal of information also exists on current usage patterns within the waters of the Northeast Shelf system. For example, Olson (2011) finds very different spatial usage patterns between individuals reporting fishing in only a single statistical area throughout the entire year, versus those reporting multiple statistical areas (Figure 4). Spatial usage patterns can be further differentiated by land-based community (St. Martin and Hall-Arber 2008), with similar ocean usage patterns likely due to networks of information sharing.

Economically, short-term impacts of marginal shifts in species distributions and expected landings can be assessed through the Northeast Region Input-Output Model (Steinback and Thunberg 2006), in terms of regional changes to income, employment, and value-added sales within the states bordering the Northeastern Shelf system. A portfolio analysis has also been

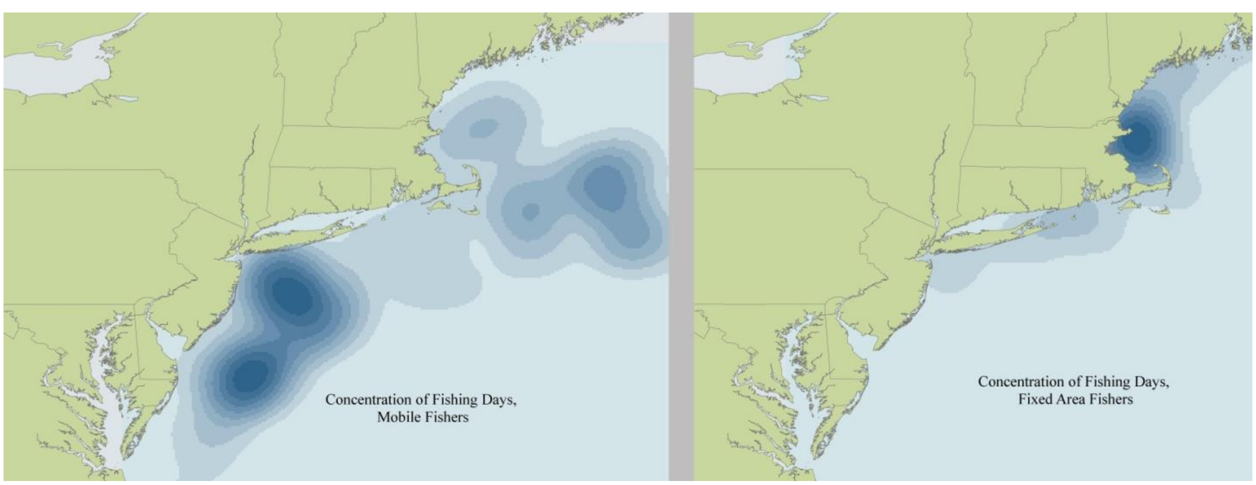

Figure 4. Spatial usage patterns for individuals reporting more than one statistical area fished in a given year on the left versus those reporting only a single statistical area fished on the right (Olson 2011)

developed to assess the trade-off between the revenue streams that can be generated from species under management and the variance around those streams (Jin et al. 2014). The analysis explicitly captures the interactions among species examined within the portfolio, and there are plans to extend this framework to specifically assess the Northeastern Shelf's risk exposure to climate change, using the impact assessment developed by Hare et al. (2014). Spatially modeling of fishing location choice will also play an important role in assessing impacts and predict responses for both commercial (Haynie and Layton 2010) and recreational fishermen (Jarvis 2011).

However, the longer-term impacts of climate change are more problematic to assess, in that they necessitate the use of data not currently gathered by NMFS on a regular basis or require model predictions out of sample. For example, different segments of a fishing fleet could respond differently to shifts in species distribution, due to changes in catchability of the future stock mix, social or cultural factors impacting desire/ability to change fishing areas, or strong preferences for fishing on certain species groups (Clay 1996). Understanding whether these differences are more likely to translate into individuals leaving a fishery, versus conversion to a more efficient gear type, depends in part on an individual's fixed costs and in part on experience and family status (e.g., the presence/absence of young children in the home). A fixed cost survey is currently being conducted, but only two years of data are currently available, for a very short window into these costs. Even less information is known for how processors and other non-harvesting sectors of the fishery complex and infrastructure will respond to changes in fish distribution and catch composition. This, in turn creates additional uncertainty for fishermen as these are important considerations in whether fishermen are likely to change ports of landing, or whether port specialization means landings will continue to be funneled in a similar pattern to today. Data on household composition and personal preferences are generally lacking, as are good demographic data on fishermen in general (especially for crew). Data for some of the fishery performance measures (financial viability, distributional outcomes, well-being, stewardship, governance) are available and can be used to track changes in individual fisheries over time (Clay et al. 2014, Murphy et al. 2014), relative to climate change measures. But data for many of the measures is lacking or has so far been collected in a first year of crew/owner surveys, with funding to make these ongoing data collection instruments still uncertain. The seafood distribution chain has begun to be mapped, though only for a few species concentrated in New England at this point.

Further, management based on species/area combinations – whether the division of FMPs across regional fishery management councils, the placement of closed areas for spawning grounds, or the assignment of ITQs to specific areas – will need updating as species change location. These types of pressures are already being seen in allocations that are made on a state-by-state basis based on historical landing patterns. In some cases species will increase or decrease stock levels, again requiring management adjustments. The resolutions of these governance issues are strongly tied to social and economic impacts and the demographic and preference data referenced above will be critical in predicting and assessing those impacts. A general overview of the types of impacts that might occur and likely governance challenges are described in Himes-Cornell and Orbach et al. (2013), especially pp. 80-100 and 127-137.

Ultimately, a more robust understanding of the long-term dynamics expected to occur due to climate change would necessitate additional investment in socio-economic data and research. One example is to develop a better understanding of port dynamics, and what factors lead to port expansion or contraction, including the interaction of the demand for port facilities by fishermen competing with other demands for port space. Models (and supporting data) that explain investment and migration decisions of fishermen are needed to predict adaptation to shifts attributed to climate change. Some of this can be accomplished through studies that combine time series with cross-sectional analysis across existing ports. Surveys that rely on choice experiments may be particularly helpful in developing estimates of fishermen and supporting industry response to expected ranges of changing conditions.

Ways Forward

Climate-ready fisheries management requires having the science, governance structure, management tools, and political will to make challenging decisions in a changing environment (Pinsky and Mantua 2014). There are multiple points for climate science information to enter living marine resource management processes that encompasses science and research as well as assessment, advice, and management decision making. Here in the Mid-Atlantic region, we start with data collection and population modeling on the science and research side, then go into a review and status determination process during the assessment and advice stage. An increasingly important part of this process which can help in particular with incorporating climate science information into stock and habitat assessments and management advice is performance evaluation or management strategy evaluation (Punt et al. 2013). Also important is continued research and continued data collected related to the effect of climate on marine resources (Hare et al 2014, McClatchie et al. 2014). Climate science and information can be incorporated at any step along the way. Because there are many ways that climate variation and climate change can affect stocks, communities, ecosystems, fisheries, and society, a critical initial step will be prioritizing which climate effects and which living marine resources will need our attention first. Risk assessment will therefore be a valuable tool to apply even before attempting to incorporate climate science information into specific stock assessments and or management advice (Gaichas et al. 2014, Hare et al. in prep). In the sections below, we outline a potential framework for incorporating climate science within stock assessment and fisheries management that makes the best use of available tools, information, and time.

It is critical that stock and habitat assessments and management in the Mid-Atlantic (and throughout the US) satisfy all National Standards, but in particular National Standards 1 and 2:

1. Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry.

2. Conservation and management measures shall be based upon the best scientific information available.

Preventing overfishing and achieving optimum yield may become increasingly difficult for stocks affected by climate variability and climate change, if these factors are not taken into account in assessment and management. Rather than considering stocks and fishing impacts on an individual basis, managers may better achieve these objectives by considering managed stocks within the context of the climate and environment, habitat and species interactions, and fishing policy and markets across managed stocks. Multispecies models can use the same methods to include environmental covariates for population dynamics of single species, but can also include changing species interactions and fisheries technical interactions simultaneously. Potential fishing policies, biological reference points, and management measures can be tested within the context of climate and environmental change and habitat and species interactions using Management Strategy Evaluation (MSE; (Smith 1994, Sainsbury 2000)). MSE simulation analyses can incorporate multiple ecological and environmental processes affecting managed stocks in order to test whether current or proposed management measures will achieve management objectives under various conditions. Used in combination, risk assessment methods and MSE can help determine which environmental effects are most important to which stocks, and which alternative models and strategies perform well (or poorly) under climate change or environmental variability (Smith et al. 2007, Sethi 2010).

Risk Assessment

Using risk assessment as a first step, limited scientific resources may be focused on a subset of high priority stocks and climate impacts can be examined with more detailed individual assessments. It is important to begin with a big-picture assessment of the economic and social importance of the stock as well as its particular vulnerabilities to the observed and projected climate variability or change. Because multiple stocks are under management, a risk assessment framework provides a useful tool for identifying both priority risks and priority stocks requiring detailed analysis (Fletcher 2005, Chin et al. 2010, Sethi 2010, Hobday et al. 2011, Pecl et al. 2011, Cormier et al. 2013). For the Mid-Atlantic region, a recent simple risk analysis applied to benthic, pelagic, and demersal fish and invertebrate communities found that commercial and non-target benthic invertebrates might be among the most sensitive species to short term predicted and observed climate impacts in the region (Gaichas et al. 2014). A fuller climate vulnerability assessment has been completed for individual species on the Northeast US shelf (Hare et al. in prep, Morrison et al. in review); this work should be used to identify priority stocks and climate impacts where stock assessments may incorporate climate information.

Incorporating climate factors into assessments, with caveats

Oceanographic/environmental conditions are important factors impacting marine fish population dynamics. A meta-analysis by (Vert Pre et al. 2013) applied to stocks in the RAM Legacy Database (a global database of stock assessment outputs, Ricard et al. 2012) found that regime shift or mixed models (combinations of regime shift and biomass dynamics models) tended to outperform simple stock assessment models when explaining changes in population productivity. That is, much of the inter-annual variability in fish productivity is better explained by environmental regime shifts (a component of climate variability) than it is by commonly assumed relationships between stock size (biomass) and productivity.

There are many ways that climate and environmental information can be included in stock assessments. Many examples from this region and others demonstrate this. In some cases, population models can be linked directly to physical or climate models (Hare et al. 2010). In other cases, selection of input data (1990-2014 vs 1998-2004) without model modification may also account for long term variability in population productivity (i.e., regime shifts) (Friedland and Hare 2007, Litzow and Mueter 2014). To date, there are examples of stock assessments incorporating climate and environmental signals in the Mid-Atlantic region including the 2014 Butterfish assessment[4] and the 2012 Southern New England Mid-Atlantic Yellowtail Flounder assessment[5]. The full assessment documents give detailed methods, but briefly in the Butterfish assessment, bottom temperature data combined with an oceanographic model were used to modify survey catchability (q) to account for how changes in thermal habitat may affect availability of butterfish to the trawl survey. In the Yellowtail Flounder assessment, a cold pool index was linked to recruitment. Although this was not used in the final assessment, evidence of linkages between the shrinking cold pool and reduced recruitment was used to select an appropriate dataset as a basis for estimating population productivity. Using the most recent recruitment data combined with evidence from climate linkages, this stock has new biomass and fishing reference points reflecting a low-productivity regime due to climate factors.

Although progress has been made, incorporating climate factors into assessments should proceed with caution. Published stock recruitment relationships with environmental covariates have often failed to hold up over time. Meyers (1998) examined stock recruitment relationships that had a significant environmental covariate, and found that over time these relationships tended to break down and the environmental covariate was, in many cases, no longer a significant predictor of recruitment. He also found that these environment-recruitment relationships are more likely to persist for stocks that are at the limit of their range. Meyers (1998) also noted that it's difficult *not* to find environmental variables that are at least nominally statistically significant. If we look at the whole suite of environmental variables that we might include in the stock assessment as a predictor of recruitment, inevitably something can be found that's significantly related. But many of these relationships are simply due to chance (Francis 2006), and when you try to apply them in the future, they will no longer remain significant. However, problems with relationships that worked in the past but no longer work are not necessarily simple statistical artifacts of over-fitting models. In some cases, the fundamental relationships can truly change. For example, one can think of an environmental factor that only becomes important at some threshold level of another environmental factor. Thus environment-productivity relationships are not expected to be constant (linear) through time, and therefore, projections about future states of nature should be interpreted with caution. Regime shift models may address this issue if we are correct in assuming that the parameters of any population dynamics model are not, in fact, constant, but can change through time. The difficulty here lies in detecting those regime shifts in time to do

[4] http://nefsc.noaa.gov/publications/crd/crd1404/
[5] http://www.nefsc.noaa.gov/nefsc/publications/crd/crd1218/

something about them. In general, our current ability to forecast regime shifts is not particularly good and we generally learn about them well after the fact.

Management strategy evaluation (MSE): key components

Using MSE to evaluate potential data collection programs, alterations to assessment models, and management policy changes is especially relevant when considering climate impacts on ecosystems, stocks, the economy and society. For example, the currently planned MSE analysis of options for setting ABCs for Atlantic mackerel in the absence of an accepted stock assessment could be extended to other data poor species. This analysis could consider whether the data-poor approaches are likely to be robust to the impacts of climate variability and change that are projected for the Mid-Atlantic region and for particular habitats and stocks. The operating model at the basis of this analysis could be a single species model. An MSE could evaluate the extent to which environmental covariates, etc, included in an assessment model are able to capture the true underlying conditions and impacts on a given stock, and what happens if we do not include changes in these relationships in the assessment. Multispecies and or ecosystem models could be used as operating models for MSE examining more general harvest policies under climate change and their relative ability to achieve biological, social, and economic objectives as habitats move and change, potentially altering species productivity, ranges, overlap, and interactions.

NEFSC and academic institutions throughout the region have considerable capability for setting up and performing MSE. Physical oceanographic, habitat, food web, single species, multispecies, economic, and ecosystem models are well developed, and process research continues to improve the models, although clearly many questions remain. A key initial step is to establish frameworks for model linking and synthesis, and for collaboration between modelers, managers, stakeholders, and policy makers to develop alternative management objectives and measures for testing and to evaluate results iteratively with scientists and modelers.

EFH Designations, Management and Conservation

EFH was first identified for Mid-Atlantic fisheries in 1998 based on data collected between 1963 and 1997. Changes in the physical and biological oceanography of the Northeast Shelf Ecosystem over the last several decades and the resulting shifts in species and habitat distributions are not reflected in these static EFH descriptions. Using more recent data and habitat characteristics (e.g., seasonal habitat requirements, prey abundance and distribution) to describe EFH could account for changing oceanographic conditions and more accurately describe the current habitats essential to Mid-Atlantic fish stocks. Considering more recent datasets and additional habitat characteristics may also improve the accuracy of EFH maps and account for changing environmental conditions that have altered the abundance and distribution of species over the last 50 years. A more strategic use of Habitat Areas of Particular Concern to highlight areas or habitat types within EFH that are ecologically important, sensitive to disturbance, or rare[6] can help partners apply conservation and management strategies to habitats

[6] 50 CFR 600.815(a)(8)

and habitat functions that are vulnerable to the effects of climate change. See Appendix 2 for more information on incorporating climate information into EFH identification and conservation.

Tools for Tracking Climate, Species Distribution, Species Productivity and Impacts

Environmental data necessary to account for a variable and changing climate abounds in the Mid-Atlantic region and on the greater Northeast US shelf. The NOAA NMFS Northeast Fisheries Science Center (NEFSC) has three publicly available environmental data repositories, described below, and many more data sources exist in this data-rich and well-studied region. The NEFSC Ecosystem Advisory is published semi-annually on the web. The latest ecosystem advisory is available at http://nefsc.noaa.gov/ecosys/advisory/current/ and the archives are available at http://nefsc.noaa.gov/ecosys/advisory/archives.html. The Ecosystem Advisory webpage includes a summary section and links with further explanation, figures, data and sources for each summarized ecosystem condition. NEFSC Ecosystem Status Report ESR (EcoAP 2012) is published approximately biennially. 2009 and 2011 (http://www.nefsc.noaa.gov/publications/crd/crd1207/crd1207.pdf) editions are available, and an update is in progress. The Ecosystem Status Report tracks ecosystem indicators related to climate forcing, physical pressures, primary and secondary production, benthic invertebrates, fish communities, protected species, human dimensions, and integrative metrics. These indicators are tracked for each of the four identified ecoregions (Scotian Shelf, Gulf of Maine, Georges Bank, Mid-Atlantic) where possible. The NEFSC Climate website http://nefsc.noaa.gov/ecosys/climate_change/index.html was launched in 2013. It summarizes climate information relevant to the Northeast shelf ecosystem.

Accounting for climate driven shifts in the distributions and productivity of important fish stocks in the mid-Atlantic region will require the recognition that seascapes are not just wet landscapes, but primarily defined by hydrographic and hydrodynamic processes. It will require the development of hydrographic information systems (HIS) appropriate for seascape management analogous to geographic information systems (GIS) that are appropriate for landscape management. Integrated Ocean Observation Systems and the numerical ocean circulation models that assimilate observations provide the basic building blocks for HIS. Recently MARACOOS partners have coupled an ocean model with a domain covering the mid-Atlantic region with atmospheric model for improved hurricane forcing and on another ongoing project a MARACOOS ocean model in the domain is being coupled to longer term climate forecasts in collaboration with GDFL. These projects lay the groundwork for a simulation platform for forecasting climate driven shifts in EFH when important features of the seabed are added and accurate niche models for species and species assemblages of interest are developed.

There have been ongoing research efforts to link population models to habitat and climate models; further priority work could be identified within an MSE framework. Fogarty et al. (2008) used an environmentally-explicit stock recruitment relationship for Atlantic Cod and coupled this to the output of climate models. They projected that Atlantic Cod distribution would move northwards out of the Southern New England region. They also projected that productivity of the population would decrease as temperature increased. A similar study was conducted by Hare et al. (2010) on Atlantic croaker. In this species recruitment increases with increasing temperature, so productivity was projected to increase and distribution was projected to move northwards. Species distribution modeling has also been used to examine the effects of climate change. Hare et al. (2012) developed a niche model for Cusk based on temperature and bottom roughness. They then used temperature from climate models to project habitat into the future. The model suggested that the amount of habitat available to Cusk will decrease and become more patchily distributed. A similar study by Lynch et al. (2014) examined Alewife and Blueback Herring. They projected changes in habitat distribution and decreases in habitat near the end of the century. Importantly, however, the results suggested that population size was an important factor in the future. Niche models have also been used in the stock assessment for butterfish (Manderson et al. in prep). A thermal niche model was used to determine the availability of the population to the trawl survey by coupling the niche model with an oceanographic model hindcast. Similarly, environmentally-explicit recruitment models are being developed for use in stock assessment; these models can also be coupled with climate models. The joint development of approaches for stock assessment and climate assessments is critical in the development of Climate Ready Ecosystem-Based Fisheries Management.

Terms of Reference (TORs) for Stock Assessments

Perhaps one of the first steps toward greater explicit consideration of climate change in stock assessments is to include a TOR related to climate. Inclusion of a climate TOR would act as a formal request to stock assessment scientists to consider climate. There is existing precedent for climate TORs. For example, the TORs for the 2013 Summer Flounder benchmark assessment included: "describe the spatial distribution of the stock over time". Climate TORs should be expanded to include evaluating potential temporal changes in productivity and evaluating environmental correlates of vital rates. At this stage, when many different approaches to incorporating climate into stock assessment are currently being developed and evaluated, climate TORs should be general enough to provide flexibility to the stock assessment scientists in how they incorporate climate.

One approach that should continue to be explored is the development of research track assessments which address climate change and proceed in parallel but separately from the operational stock assessments. Under this approach stock assessment scientists and oceanographers could work together to develop new approaches to incorporating climate change into assessments. Once sufficiently ground tested and robust, the new models could then be utilized in an operational stock assessment. This is similar to the process that led to the inclusion of environmental factors in the 2013 Butterfish stock assessment.

How might Council Risk Policy adjust to climate change?

The risk policy is the Council's articulation of the acceptable risk of overfishing (P-star, which is not a scientific decision) as a function of stock biomass relative to the B_{msy}. As biomass relative to B_{msy} declines, so does the acceptable risk of overfishing. The risk of overfishing is reduced by adding a buffer to the overfishing limit (OFL) to arrive at the acceptable biological catch (ABC).

The OFL has some uncertainty associated with it which is either estimated directly within the stock assessment model or is determined by the Scientific and Statistical Committee (SSC), depending on the types of uncertainty that are incorporated in the stock assessment. The size of the buffer for scientific uncertainty between the OFL and (ABC) depends on the uncertainty associated with the estimate of the OFL. Greater uncertainty in the OFL results in a greater buffer between the OFL and the ABC.

One potential approach to incorporating climate considerations is to make adjustments to P-star within the existing OFL/ABC framework and risk policy for stocks formally defined as climate-sensitive. The NMFS Fisheries Climate Vulnerability Assessment could be used to identify stocks that are particularly climate-sensitive. All stocks are climate-sensitive to some degree, so a strict definition of what it means to be climate-sensitive will be required. If the stock assessment incorporates climate directly, then a smaller buffer between the ABC and the OFL may be appropriate. For stocks that are strongly impacted by climate change, current buffers may not be adequate for assessments that don't explicitly include climate or environmental variables.

Conclusions

Despite the clear impacts, climate is not explicitly considered in traditional fisheries management, but efforts have begun around the world to integrate climate adaptation into management activities. A range of opportunities now exists for fostering "climate-ready" fisheries into the future (Pinsky and Mantua 2014). Adapting fisheries management will likely require both anticipating climate impacts where possible to guide preparations, monitoring, and long-term planning; and maintaining management flexibility, ecosystem monitoring, and rapid-response capabilities to adapt quickly when ecosystems change unexpectedly. Emerging experiments around the world can be summarized as eight adaptation approaches that together constitute a "toolbox" of strategies. Which approach or approaches will be most useful in any given situation will depend on social and ecological context:

- Mitigate cumulative impacts on fish stocks in marine ecosystems
- Prepare for sustainable management of emerging fisheries
- Adjust reference points as the environment changes
- Move targeted conservation areas when needed, but leave broad-purpose areas in place
- Prepare international agreements for shifts in species distributions
- Evaluate management against a range of regional climate change scenarios
- Integrate monitoring and evaluation of climate and ecosystem states into the management cycle
- Reduce barriers to individual-level adaptation where possible

These strategies are not meant to be a complete set of all potential approaches, but can provide guidance and a useful starting place for adaptation thinking. Considerable research, experimentation, and practice are also needed to implement these strategies. In addition, continued innovation, research, and experimentation will be required as fisheries managers grapple with the challenges posed by changing oceans, particularly as the impacts of anthropogenic climate change become more severe.

Fisheries provide valuable ecosystem services, including a crucial source of protein for 60% of the world's population and livelihood support for more than one in every ten people alive today. Maintaining these ecosystem services will require a range of adaptation measures that both sustain ecosystem productivity and support the social and economic systems that capture these services. Long-term, however, the limits to adaptation remain uncertain, and efforts to mitigate and reduce anthropogenic climate change and ocean acidification should remain a critical part of the discussion.

The Mid-Atlantic Council manages a portfolio of fishery resources with vastly different life history strategies ranging from short-lived squid species which complete their life cycles in one year or less to ocean quahogs, which are the longest living animal species on the planet. In terms of habitat use, the species managed by the Council likewise occupy a wide and diverse range of habitats including shallow inshore estuarine areas to the depths of the submarine canyons on the edges of the continental shelf. The geographic range of all of the species managed by the Council extend well beyond the geographic statutory authority defined in the Magnuson Act (New York to North Carolina) and some have a significant portion of their populations which straddle US and Canadian waters. So too are the fisheries diverse, ranging from small scale hook and line fishing for recreation to medium-large scale industrial fisheries which employ a broad range of fixed and mobile gear types. Given these attributes and the highly dynamic nature of the physical oceanography of this region, the Council will require a diverse set of tools to deal with climate variability and change as it moves forward. To prepare for future change and variability in climate and the anticipated impacts on fish stocks and the fisheries they support, the Council should consider evaluation of these effects within the context of the "climate-ready" check list outlined in the Table 1 below in its EAFM Guidance Document.

Table 1. Climate Ready Fishery Science and Management Checklist

What	Where	How
Vulnerability assessment	NOAA/NEFSC; EAFM Doc	Identify species at greatest risk to climate change and variability
Stock ID and unit area	Stock assessment and FMP	Assessment TOR; update FMP periodically
Changes in Productivity	Stock assessment and FMP	Monitor vital stock parameters (SA TOR); update BRPs periodically
Species/habitat interactions	SA/FMP/EAFM Document	Quantify habitat and productivity linkages (modeling); EFH designations
Fleet dynamics	FMP/EAFM Document	Build MSE analytical capacity; track fleet performance
Fisheries interactions	NEFOP and FMP	Monitor bycatch; implement adaptive management measures
Joint management	Inter-jurisdictional partnerships	Climate Committee; adaptive management; International treaties
Climate Risk Analysis	FMP/EAFM Document	Evaluate alternative management measures relative to risks of climate change
Ecosystem Status	NEFSC Ecosystem Report	Continue ecosystem observing programs and reporting
Ecosystem Productivity	Future FEP	Develop full ecosystem models (e.g., Atlantis); track ecosystem structure, function and productivity

Effects of climate velocity on fish and fisheries

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By 2100, global temperatures are projected to be 2-4°C warmer and ocean waters are expected to be substantially more acidic than they are today, with profound effects on natural ecosystems and human societies. The world is now committed to at least a substantial portion of these changes even if rapid mitigation measures are taken, and society is beginning to consider not only what impacts to expect, but also how to adapt to those impacts.

One particularly useful way to understand the impacts of changing temperatures is in terms of climate velocity. Climate velocity measures the speed and direction that an isotherm (line of equal temperature) moves across the landscape, which is therefore the same rate and direction that a species would have to shift to maintain a constant thermal environment. Climate velocities are as fast, and sometimes faster, in the ocean than they are on land. Median velocities from 1960-2009 in the ocean have been 21.7 km/decade, but reached 200 km/decade in some regions.

Both in the U.S. and around the world, clear indications can be found of populations shifting to follow changes in temperature. In the northeast U.S., species like summer flounder have shifted north 120 km over the last four decades, consistent with rapidly warming temperatures in the region. This pattern appears across a wide range of species in the northeast U.S. that are caught in scientific bottom trawl surveys (on average, shifting 20 km per decade northeast), as well as throughout North America. For example, while species have been shifting south in some continental shelf regions of North America (e.g., west coast or Gulf of Alaska), these tend to be regions where temperatures are cooling. Similarly, changing temperatures appear well correlated to changes in depth, with species assemblages moving deeper in regions of warming temperature and moving towards shallower depths in regions of cooling temperatures.

Scientific bottom trawl surveys also suggest that the rate and direction at which species distributions have shifted over the past two to four decades is closely correlated to local climate velocities. This pattern holds up continent-wide across 325 taxa captured in nine surveys (U.S. and Canada), as well as across species within regions. The thermal envelope for longfin squid has shifted south over the last 40 years in the Northeast U.S., and squid have shifted south as well. Similarly, the thermal envelope for monkfish has moved north, and monkfish have shifted north as well.

Fisheries respond to these changes in the ecosystem, including by following fish poleward and by changing the mix of species caught in any particular location. However, these changes in fisheries are mediated by constraints imposed by regulations, economics, and social factors. For example, summer flounder have shifted north, and analyses of summer flounder fishery landings show that landings have also shifted north. However, there is substantially more variability in the mean latitude of summer flounder landings before the early 1990s, and substantially less variability after this time. This change appears to coincide closely with the implementation of Amendment 2 in the summer flounder fishery management plan, which set a state-by-state allocation of the summer flounder quota. Overall, the mean latitude of the summer flounder fishery landings have not moved north as fast as the mean latitude of the summer flounder population (in fact, 68% slower). Similar examples of fishery landings lagging behind shifting fish have been observed in red hake, American lobster, and yellowtail flounder fisheries.

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Appendix 1. Management and Governance Workshop Summary

In March 2014, the Mid-Atlantic Fishery Management Council convened more than 70 fishery managers, scientists, policy makers, and stakeholders for a 3-day working in Washington, D.C. to examine the governance implications of climate change for East Coast marine fisheries. East Coast fishery management partners participate in managing 49 different federal and interstate fishery management plans, many of which include multiple species and stocks. The alignment of species distributions with management jurisdictions, the diverse and often complicated life histories of managed species, and interactions between fisheries frequently require collaboration among management partners. This complex system of authority and responsibility, information, and interests involves a corresponding network of interactions between management partners. This governance complexity is overlaid with management complexity, which derives from the wide range of biological, ecological, social, and economic management objectives identified for Atlantic Coast fisheries, and the array of tools used to support them. By changing the distribution and abundance of fish stocks, climate change will introduce even greater complexity and uncertainty into an already complicated management process.

This workshop was designed to leverage the collective knowledge and expertise of participants, and take a cross-cutting look across fisheries to identify concerns and potential pathways forward. The overarching goal was to provide fishery managers with the opportunity to identify existing and potential climate-related impacts on the management and governance of East Coast marine fisheries, and explore next steps and pathways for responding.

The specific objectives of the workshop were:

- Explore the existing and potential impacts of climate change on the management and governance of East Coast marine fisheries, with an emphasis on the policy implications of shifting fishery distributions and changing productivity;
- Evaluate processes for documenting and acknowledging climate-related changes and initiating a management response;
- Identify key management questions, concerns, and information needs to guide future research and coordination between management bodies;
- Examine the flexibility of the existing management framework to accommodate climate-related governance challenges; and
- Discuss potential solutions and next steps for adapting and responding to climate change, and identify opportunities to maintain a dialogue between East Coast fishery management partners.

Through a series of facilitated discussions, participants shared experiences within and between regions to characterize the issues and the decision-making environment with regard to climate change. Workshop participants identified a wide range of climate change impacts and concerns, confirming that many of the issues being explored in the climate science realm have also entered the management discourse.

Workshop participants identified a wide range of climate change impacts and concerns, confirming that many of the issues being explored in the climate science realm have also entered the management discourse. Many of these concerns fall under the larger umbrellas of changing fishery productivity and shifting fishery distributions, but demonstrate that climate change impacts can take many forms. Of greatest concern to managers are the increase in scientific uncertainty, and the possibility of permanent tipping points. The management implications of these impacts could include jurisdictional disconnects, misalignment between science and management within the fisheries management enterprise, and diminished management effectiveness; in sum, the performance of our entire management system. These concerns reinforce that climate change is not a single issue, but a dynamic condition that must be taken into consideration for the management process to succeed.

Adapting and responding to climate change could involve changes to governance as well as changes to management. Discussions reinforced the value of considering all of the potential pathways for response, and the timelines, processes, and outcomes involved. Responding to climate change may also involve other aspects of the management process, in particular how priorities and concerns are communicated to stakeholders and beyond the fisheries realm. Finally, developing a climate change response is not just a matter of connecting problems with solutions. Participants emphasized that there are also impediments and risks to initiating a management response.

Participants also explored the qualities of responsive management, and what it means to be well equipped to respond to climate change. Participants identified the attributes of management tools that facilitate or constrain flexibility, and considered how to instill qualities of resilience, flexibility, and responsiveness. Looking ahead, it's important to plan now for the challenges of emerging and shifting fisheries, and ensure that the interests of states and stakeholders are represented. Climate change response also depends on building the scientific foundation to support informed decision-making. Participants identified a broad range of information needs, suggested strategies for improving the alignment of climate science with management needs, and reinforced the synergies between climate change response and ecosystem-based management.

Climate-ready fisheries management requires having the science, governance structure, management tools, and support and political will to make challenging decisions in a changing environment. During the latter part of the workshop, discussions transitioned from framing the issue toward identifying potential next steps, solutions, and strategies for supporting climate change response.

Appendix 2. Incorporating variable and changing climate and environmental conditions into essential fish habitat (EFH) designations and conservation

Current EFH identifications in the Mid-Atlantic region

EFH was first identified for MAFMC fisheries in 1998. Since that time, only tilefish EFH has been updated. The 1998 EFH identifications are based on long-term and historic data sets. Maps of juvenile and adult EFH are based on data from the 1963 - 1997 NMFS bottom trawl survey while maps of egg and larval EFH are based on data from the NMFS Marine Resources Monitoring, Assessment and Prediction (MARMAP) 1977 - 1987 ichthyoplankton survey. These surveys are applied on a year-round basis (not seasonal) and include the average catch rates (numbers per tow) by ten minute squares (tms) of latitude and longitude (size = 75 sq miles). Additional sources of information were used to identify EFH within inshore areas. These sources are comprised of data collected during surveys that spanned 1978 - 1997. These data provide levels 1 (distribution of the species for some or all of the geographic range) and 2 (habitat-related species density) EFH information.

Text descriptions for individual species and lifestages include several additional habitat characteristics beyond abundance and distribution, including depth, temperature, and salinity ranges. For benthic life stages substrate and vegetation associations are also included.

Accounting for changing climate conditions: EFH identification

The Council has several options to improve EFH identifications to better represent the distribution of essential habitats for its managed species. Considering more recent datasets and additional habitat characteristics will improve the accuracy of EFH maps and account for changing environmental conditions that have altered the abundance and distribution of species over the last 50 years.

Updated time series data

Changes in oceanographic conditions in the north and mid-Atlantic regions over the last several decades have altered the distribution of fish species, including northward shifts of stocks in the Mid-Atlantic Bight (Nye et al. 2009)[7]. The MARMAP and bottom trawl survey data used in the 1998 EFH identifications do not account for observed interrannual or decadal shifts in species distributions and abundance. Distribution and abundance data from these datasets no longer accurately represent the current habitat conditions for MAFMC-managed fisheries, making the 1998 EFH designations severely outdated. Using more recent trawl survey and MARMAP data to describe EFH based on habitat-related species density would account for changing oceanographic conditions and more accurately describe the modern day habitats essential to mid-Atlantic fish stocks.

[7] Nye JA, Link JS, Hare JA, Overholtz WJ. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Mar Ecol Prog Ser 393:111-129

Thermal habitat

While the text descriptions include information on the required temperature ranges for each lifestage, thermal habitat distribution was not considered in the bottom trawl or MARMAP surveys, resulting in EFH maps that do not reflect the current conditions constraining the distribution and productivity of some species. Analyzing the overlap of expected thermal habitat distributions with other habitat and seabed features could help the MAFMC better forecast the expected distribution of managed species and improve EFH identifications.

Habitat suitability and distribution

While the thermal and hydrodynamic properties of the ocean drive growth rates and distribution of mid-Atlantic fish species, these properties also influence the distribution of biogenic habitats within the region. Since several mid-Atlantic fisheries use and/or depend on biogenic habitats like seagrass, oyster reefs, and deep-sea coral habitats, the availability of suitable substrates within critical thermal ranges will be important factors influencing the health and productivity of some fish stocks. The overlap between these habitat features are important factors that the MAFMC can consider when identifying EFH.

Prey abundance and distribution

The EFH regulatory guidelines allow for the inclusion of prey species as a component of EFH because of the important role they play in providing essential feeding habitat for managed species[8]. The abundance and distribution of prey species are shifting with changing thermal conditions. Areas with thermal and substrate characteristics important to a species may not be productive habitat if the habitats do not support its prey. Areas of overlap between suitable thermal habitat, substrate, and prey availability should be considered when identifying EFH.

Habitat Areas of Particular Concern

The EFH regulatory guidelines allow for fishery management councils to identify Habitat Areas of Particular Concern (HAPCs) to highlight areas or habitat types within EFH that are ecologically important, sensitive to disturbance, or rare[9]. The MAFMC has used this authority sparingly in the past, identifying HAPCs for summer flounder and tilefish. As changing oceanographic conditions continue to affect the distribution of species managed by the South Atlantic, Mid-Atlantic, and New England Fishery Management Councils and their habitats, the identification of HAPCs that provide essential habitat functions to one or many fisheries will become even more important to help focus habitat conservation where it is most needed. The MAFMC has several options for considering climate change when designating HAPCs. Options include, but are not limited to, the following:

- Identify climate-vulnerable habitats and/or areas as HAPCs. These “climate hotspots” may be areas of importance to one or many MAFMC species and/or lifestages that are likely to encounter the most pronounced effects of climate change, including increased temperature or sea level rise. Habitat areas and/or types that are less resilient to these affects may require enhanced protection. Those that are most resilient may be able to

[8] 50 CFR 600.815(a)(7)

[9] 50 CFR 600.815(a)(8)

support some compatible uses and tolerate low-level impacts from fishing and non-fishing activities.
- Identify “habitat hotspots” as HAPCs. These may include areas of overlap between suitable substrate and thermal habitat, prey availability, and distribution of the managed species.

In all cases, it will be important to identify the objective of the HAPC to guide habitat conservation and management decisions. For example, identifying the habitat function that is vulnerable to the effects of climate change can help NMFS and other state and federal agencies determine the most appropriate protection and/or restoration strategy for the area.

Additional considerations and constraints on EFH identifications:

The EFH regulatory guidelines outline specific requirements for EFH text descriptions and maps. Fishery Management Plans must describe EFH in text including reference to the geographic location or extent of EFH using boundaries such as longitude and latitude, isotherms, isobaths, political boundaries, and major landmarks[10]. EFH text descriptions should explain pertinent physical, chemical, and biological characteristics of EFH for the managed species and explain any variability in habitat usage patterns, but the boundaries of EFH should be static. FMPs must also include maps of EFH that display, within the constraints of available information, the geographic locations of EFH or the geographic boundaries within which EFH for each species and life stage is found. Maps should identify the different types of habitat designated as EFH to the extent possible[11].

Under these regulatory guidelines, the Council can:

- include the thermal, salinity, and dissolved oxygen habitat requirements of a species in its EFH description;
- describe seasonal habitat needs in a species’ EFH text description, but include the full range of habitat needs in the map of the species’ EFH;
- base EFH maps on more recent data that reflects current species and habitat distributions.
- account for temporal changes in species distributions due to climate changes (trends) and changes in stock abundance (fluctuations);
- identify HAPCs in hotspots of change or in areas that provide the most habitat functions for a species (e.g., areas of overlap between substrate and thermal habitat, prey distribution, and managed-species distribution);
- develop hydrographic information systems (HIS) appropriate for seascape management; and
- ensure that EFH and HAPC information is reviewed at least every 5 years so that the most up-to-date habitat and species abundance and distribution data are used to identify and describe EFH.

Accounting for changing climate conditions: EFH conservation

[10] 50 CFR 600.815 (a)(1)(iv)(B)
[11] 50 CFR 600.815 (a)(1)(v)

Beyond ensuring the most up-to-date and critical habitat information is used to identify and describe EFH, NMFS and the MAFMC has several options to improve the conservation and management of EFH in the face of changing climate and oceanographic conditions. Both organizations can be more precautionary in the face of climate-driven impacts to improve species resiliency to changes.

NMFS habitat conservation options

NMFS can consider thermal habitat requirements when reviewing and commenting on state and federal activities that may affect EFH. Through the EFH consultation, NMFS can be more protective of areas providing critical thermal habitat that constrains the species' distribution. Given the constraints of more limited thermal habitat availability, NMFS can consider protecting movement corridors or use its habitat restoration programs to improve habitat connectivity and facilitate the movement of displaced organisms. NMFS can also be more precautionary when recommending mechanisms to minimize adverse effects to EFH, such as recommending buffers around high-quality habitats.

MAFMC habitat conservation options

The MAFMC can be more engaged in habitat conservation activities to improve the resiliency of its fisheries to climate change. For example, the MAFMC can identify or recommend measures to mitigate impacts from non-fishing activities (such as development projects that have long-time horizons, fossil fuel and nuclear power plants, hydropower, road and highways projects) to climate vulnerable habitats or hot-spots for change. The MAFMC can also consider expanding its partnerships so that other organizations with the ability to influence habitats can advocate on behalf of mid-Atlantic fisheries and their habitat needs.

Research needs

There are several research areas that will inform and improve our ability to identify, describe, and conserve EFH in the face of climate change. The following research activities may be necessary:

- Collect more habitat condition and distribution data (e.g., bottom temperature, emergent and submerged vegetation, salinity), especially in nearshore juvenile nursery areas.
- Develop models of expected resource productivity under various habitat scenarios (e.g., abundant moderate-quality habitat vs. scarce high quality habitat. Are there multiple types of habitat that can fulfill similar functions?).
- Develop hydrographic information systems (HIS) appropriate for seascape management analogous to geographic information systems (GIS) that are appropriate for landscape management.
- Monitor shifts in species distributions/model attribution of changing distributions (i.e., natural and anthropogenic drivers).