Near-term forecasts of species distributions for fisheries management

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A. Project Description

Purpose

This project will develop and test process-based methods for forecasting the geographic distribution of marine fishes and invertebrates over 1-10 year time-scales to inform decisions about spatial closures, emerging fisheries, stock boundaries, and potential conflicts among ocean resource users.

Background

As climate change proceeds, one of the most dramatic responses has been marine species shifting into new territory and away from traditional territory. These changes are happening an order of magnitude faster in the ocean than on land and are creating challenges for fisheries management and marine conservation. The goal of this research is to provide ecological tools for near term (1-10 years) fisheries and marine conservation planning.

Shifting species create a number of conservation and management challenges. In the North Sea, warming temperatures pushed juvenile place deeper and out of the closed area designed to protect them from fishing. In the Mid-Atlantic Bight, tilefish shifted north of Cape Hatteras, NC and sparked an unregulated fishery for at least a decade before fisheries managers realized the fishery was operating. Also in the Northeast U.S., a decade of rapid warming has reduced the available habitat, productivity, and recruitment of American lobster and driven fishery collapses in Long Island Sound and elsewhere in Southern New England.

In a general sense, we know that these changes are ongoing and will continue. Climate change projections are widely available out to 2100, and more recently, projections of species habitat at the multi-decadal to century time-scale have also become available (*1*). These data are useful in a strategic sense for conservation planning and fisheries management. The Mid-Atlantic Fisheries Management Council (MAFMC), for example, explicitly includes long-term habitat projections in their Ecosystem Approach to Fisheries Management (EAFM) Guidance Document, particularly as a way to identify priority species for adaptation of fisheries management to climate change, clarify long-term risks, and identify future issues (*2*).

However, the bulk of fisheries management decisions are made on relatively short time-scales, typically one to a few years. Decisions about reference points, catch limits, quota allocations, bycatch measures, temporal and spatial closures, and effort restrictions are often made for the coming year or for the coming few years (*3*). Many stock assessments in the northeast U.S., for example, make three-year projections to guide such decisions. When it comes to shifting species distributions, there is therefore a clear need to "meet managers where they are" and provide relevant information on the annual to multi-annual timescale (*3, 4*). Helping managers think about adaptation to climate variability at short timescales may also help them think about longer-term climate adaptation (*3*).

We are at a key moment in time when rapid progress can be made on this problem. Skillful forecasts of oceanographic conditions are now available for the coming year, decade, and even multiple decades in some cases, depending on the particular oceanographic condition and region of interest (*4, 5*). The slow dynamics and long memory of the ocean make such forecasts possible, in stark contrast to the challenges forecasting atmospheric conditions (*4*). The

North Atlantic stands out as a region were ocean temperatures are predictable for several years to a decade, in part because of the slow dynamics of the Atlantic Meridional Overturning Circulation (AMOC) (*3, 5*). NOAA's Climate Program Office has also funded an ongoing project at the Woods Hole Oceanographic Institute (WHOI) to improve interannual forecasts of ocean temperatures on the Northeast U.S. continental shelf (Jon Hare, pers. comm.).

The science gap comes in translating these predictable oceanographic conditions into useful predictions of species distributions. Statistical descriptions of species habitat can and have been made at seasonal timescales for, e.g., bluefin tuna (*3*), but a key assumption of such models is that species are in equilibrium with their habitat. It is precisely at annual to decadal timescales that species are unlikely to meet such an assumption, since many species grow, disperse, and reproduce at annual time-scaless (*6*). Improved forecasts will therefore depend on improved consideration of the ecological processes that affect and change species distributions (*4, 6*).

This project will fill this gap by developing mechanistic models for species distributions—termed dynamic range models—that include species growth, dispersal, mortality, reproduction, and the influence of the environment. We will develop these as generic models and methods applicable to a wide range of coastal marine species targeted by fisheries and by conservation efforts. However, we will focus on four case study species (summer flounder, spiny dogfish, shortfin squid, and grey triggerfish) for testing the prediction systems across a range of life history types and across species with immediate management use for this information. Brandon Muffley, fisheries management specialist from the MAFMC, will be part of our project team, will help tailor the research to ensure utility for decision-making, and will coordinate integration of the results into the MAFMC's ongoing EAFM process. With Muffley, we have identified decisions about annual specifications of catch limits, about allocations, about the ecosystem considerations process, and about spatial planning for offshore energy as key points where the forecast system will be useful for MAFMC decision-making.

Context

a. Management and decision-making landscape

The MAFMC is keenly interested in climate adaptation, most recently as evidenced by the development of their Ecosystem Approach to Fisheries Management (EAFM) Guidance Document (*2*). This document informs MAFMC policy with respect to the incorporation of ecosystem considerations into its current management programs. Foremost amongst these considerations are the impacts of climate change on the ocean environment and the associated impacts on fish populations. For example, the MAFMC EAFM Risk Assessment stated that, "All Mid-Atlantic species with the exception of golden tilefish had either high or very high risk of distribution shifts in the Northeast US" (*7*).

The EAFM Guidance Document and Risk Assessment in turn were inspired by the MAFMC Visioning Project, a project that shaped the future course of marine fisheries management in the Mid-Atlantic based on constituent input (*8*). The visioning 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, into fishery stock assessments and MAFMC management policy.

The impacts of ocean warming on fishery resources under the management purview of the MAFMC are already manifesting as changes in stock distribution and productivity, and in the temporal and spatial interactions among species and fisheries. These changes in vital population parameters have a cascading effect on the specification of biological reference points (overfishing levels) and stock identification/unit area definitions required for managed species. In addition to biological impacts, distributional shifts from a warming ocean create management challenges by confounding areal or seasonal quota allocations that are based on historical catches, by changing the impacts of closed areas, and by altering the allocation among directed versus incidental fisheries due to changing species assemblages and discarding patterns. A 2016 letter from the New England Congressional delegation to the Secretary of Commerce about changing species distributions, a 2017 Secretary of Commerce ruling to overturn an Atlantic States Marine Fisheries Commission (ASMFC) conservation decision based on shifts in species distribution, Sen. Chuck Schumer's "Fluke Fairness Act" , and talk of a New York State lawsuit over shifting species distributions are all evidence of the extent to which shifting species are creating management challenges in the Northeast U.S.

To help adapt to these challenges, MAFMC and other Atlantic coast managers identified projections of climate-driven changes in fisheries (and uncertainty in these projections) as key needs so that all fisheries stakeholders can consider and plan for the effects of climate change (*9*). Managers currently have access to historical information and long-term strategic information on species distributions and habitat (*1*). However, management decisions are typically made over 1- to 5-year time horizons. Near-term projections of species distributions would be more in line with how the MAFMC operates and would have a greater impact on day-to-day decisions in the MAFMC.

The MAFMC currently uses annual State of the Ecosystem reports and twice-annual Ecosystem Status Reports as ecosystem context for its management decisions, but quantitative information on near-term species distributions are not part of this report. Our goal will be to produce a forecast system that can be included in the State of the Ecosystem report each year.

With Brandon Muffley, we have identified four kinds of decisions to be informed by the forecasts. In general, we will aim to provide information that will 1) inform allocation decisions, 2) inform the ecosystem considerations process, 3) help guide the annual specifications of catch limits, and 4) guide spatial planning for offshore energy development. The MAFMC is currently developing allocation scenarios for summer flounder, and the forecasts will be directly applicable to this process. Summer flounder have also been identified as a priority for the MAFMC's EAFM process, the next step of which is to develop a conceptual model and then an ecosystem-based management strategy evaluation (MSE) over the next couple years. This summer flounder MSE will include climate considerations, and we will work to integrate the forecast system into this process.

For spiny dogfish and squid, benchmark stock assessments are planned for 2021. Our goal will be to include the forecast system in the stock assessment forecasts, in particular through refined estimates of catchability and future biomass distributions.

For grey triggerfish, the MAFMC is evaluating whether and how to start managing the stock. Currently, the South Atlantic Fisheries Management Council (SAFMC) manages grey triggerfish south of Cape Hatteras, but grey triggerfish are now also being landed in Virginia. The MAFMC hopes to avoid an emergency rulemaking scenario like they had to implement for blueline tilefish in 2015. The forecast system can help them decide when and how to begin management measures.

b. Current engagement

This proposal was motivated by the May 2018 COMPASS workshop "Fishing for Solutions in a Changing Ocean" in Washington, DC, and discussions there with fisheries managers and scientists, including Mike Luisi (MAFMC chairman), Toni Kerns (Atlantic States Marine Fisheries Commission staff), and Bill Tweit (North Pacific Fishery Management Council interim chair). Follow-up conversations with Dr. Jon Hare (Director, Northeast Fisheries Science Center [NEFSC]), Brandon Muffley (Fishery Management Specialist, MAFMC), and Vince Saba (NEFSC) helped to refine the project.

Three themes emerged from these conversations. First, near-term information is of more direct utility to fisheries management and their day-to-day decisions than long-term, strategic information. Near-term forecasts, even if uncertain, can also help managers learn how to incorporate long-term climate information into fisheries management. Second, forecasts based on demographic principles like growth and recruitment are more likely to be trusted and used by MAFMC members, since they are already familiar with stock assessments based upon similar principles. Third, geographic shifts in species distribution are already a top concern for the MAFMC and an active area of climate adaptation. Tools to help the MAFMC make effective decisions on this topic are likely to be used. The case study species and management decision points discussed below were chosen in discussions with Brandon Muffley based on their importance to the MAFMC.

Research Question(s)

1. To what extent can dynamic range models accurately forecast changes in species geographic distributions?
    - H1: Dynamic range models provide greater skill than statistical species distribution models and persistence forecasts
2. At what time-scales do dynamic range models provide skillful forecasts?
    - H2: Dynamic range models are most useful over the 2-5 year time horizon over which transient ecological dynamics are important and multi-annual climate forecasts are reasonably accurate
3. Does information on fishing pressure improve forecasts of species distributions?
    - H3: Interactions with fishing provides improved forecast skill for some but not all species

Research Methods and Analyses

Our basic approach will be to compare dynamic range model forecasts against historical observations of species distributions and against other forecast methods, test the ability of dynamic range models to project species distributions over 1-10 year time horizons, and extend the dynamic range modeling approach to include fisheries interactions. We will use summer flounder, spiny dogfish, squid, and grey triggerfish as our focal species. The goal is to prototype a near-term ecological forecast system that will have high utility to the MAFMC and that can be easily expanded to other fisheries and management organizations.

c. Dynamic range models

A long-standing concern with standard bioclimate envelope models is that they do not account for the underlying population dynamics that constrain or change species geographic distributions. These non-equilibrium dynamics violate the assumptions of bioclimate envelope models and can cause biased estimation of thermal envelopes. These concerns are of somewhat lesser importance over long time horizons (decades to centuries) but are very prominent for near-term dynamics (months to years). Accounting for the joint effects of thermal niche and spatial population dynamics (growth and dispersal) during data analysis has traditionally been difficult, but a newly available method makes this possible. We will use dynamic range modeling, which uses a Bayesian framework to jointly estimate spatial population dynamics and the variation of demographic rates in response to the environment (*10*). Such models serve as a process-based link between climate and population dynamics.

We will use a model structured by locations and size classes where $N_{i,k,t}$ is the number of individuals at location i in size class k at time t. Our base model will use 1° latitude x 1° longitude grid cells from Florida to Nova Scotia for locations, three size classes as a balance between specificity and complexity, size class transition rates $g_{k1,k2}$, mortality m_k, adult movement to each of the A adjacent patches at rate f, and recruitment $\alpha(N_{i,3,t}, T_{i,t})$ that depends on adult population size and temperature $T_{i,t}$ (Fig. 1). The recruitment function will be density-dependent and will initially have a Gaussian response to temperature. We will also examine other functional forms for α, such as a left-skewed normal and test whether including the previous winter's minimum temperature, the previous summer's maximum temperature, or oxygen concentrations improves model fit (*1, 11*).

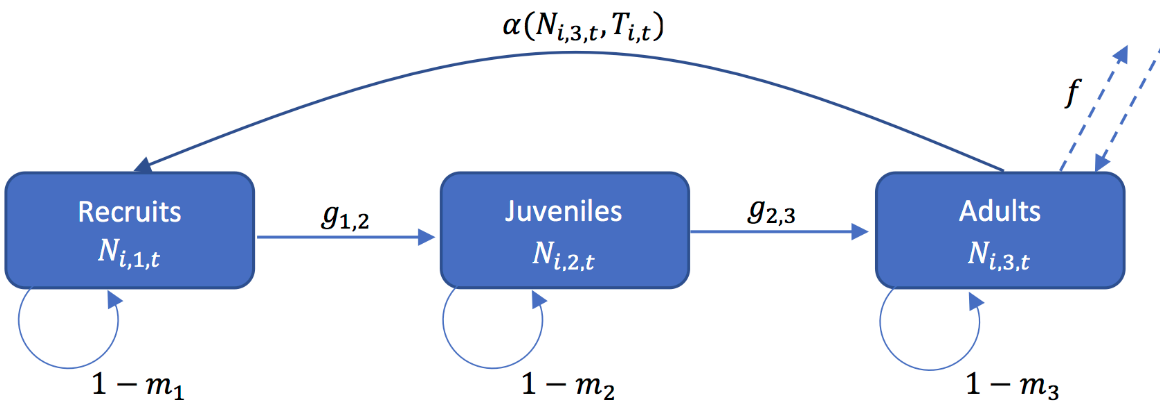

Figure 1. Our basic model structure for three size classes k, locations i, and times t.

We will refine our base model in collaboration with Brandon Muffley during regular conference calls and with stakeholders during our first annual meeting. For example, the spatial extent or grid cell size can be adjusted based on management needs to balance tractable model estimation against precision. We will also explore whether it is valuable to include benthic habitat such as bottom rugosity or sediment grain size (*1*) in the recruitment term. The precise model formulations will likely vary among our four focal species.

Posterior distributions for the parameters will be solved using an Approximate Bayesian Computation approach (*12*). Simulations of statistical power with dynamic range models show that 10 years of data and sparse sampling (data on abundance in <5% of locations) are sufficient for accurate posteriors (*10*). In contrast, we have substantially more data: five decades of biomass data in every location in every year. We will fit the model against size-specific abundance data from the Northeast Fisheries Science Center, NEAMAP, and state bottom trawl surveys, which started in 1963 and continue in fall and spring each year. Monthly temperature and oxygen reconstructions are available from high-resolution ocean model hindcasts for the region (*13, 14*) and from global ocean reanalysis products (*15*).

The model and its forecasts will be housed in a publicly accessible Github repository written in Python. Maps, graphs and other forecast products can therefore be easily incorporated into annual State of the Ecosystem reports or other communication products.

d. Focal species

We will focus on four species managed by the MAFMC that contrast in generation time, climate impacts, fishing pressure, and ecosystem role. However, the methods are highly general, and should be applicable to any species for which historical distribution data are available.

Shortfin squid (*Illex illecebrosus*) have lifespans under a year and are highly mobile, pelagic, schooling animals. They lay pelagic eggs and move offshore as adults during the winter. They are considered an important forage species in the Mid-Atlantic and are managed with these ecosystem considerations in mind (*2*). Given their short lifespan and high mobility, they are the most likely of the focal species to track their thermal habitat closely. Projections suggest that future habitat will expand substantially in the northeast U.S. for shortfin squid (*1*). The forecasts will be useful for managing interactions with other fisheries and for designing the benchmark stock assessment scheduled for 2021.

In contrast, spiny dogfish (*Squalus acanthias*) live up to 40 years and projections are that habitat in the northeast U.S. will decline for them by 2100 (*1*). Maturity typically isn't until 12 years old and they produce about 7 pups, leading to a slow population growth rate for this species. The adults move north and south seasonally. The forecasts will be useful for examining interactions with other species (dogfish are an important predator) and for designing the benchmark stock assessment scheduled for 2021.

Summer flounder is a highly valuable and historically contentious fishery in the Mid-Atlantic. From 1968-2009, summer flounder biomass shifted north by more than 100 km (*16*). This shifts was well predicted by movements of the species' thermal envelope (*17*), but recovery from overfishing also played an important role in the northward shift (*18*). Large summer flounder are found further north, and the number of large summer flounder has increased over the last 25 years as the population has recovered from overfishing. Summer flounder migrate inshore and offshore seasonally, have broad diets, and are prey for a wide range of species (*19*). The forecasts will help design the ecosystem Management Strategy Evaluation (MSE) that is being constructed for summer flounder, as well as for the design of a state-by-state allocation system that the MAFMC is currently considering.

Grey triggerfish (*Balistes capriscus*) are of strong interest to the MAFMC because they appear to be moving into the Mid-Atlantic Bight. While historically a Gulf of Mexico and South Atlantic species, landings have recently been reported from Virginia. When, if, and how to begin managing this species can be informed by the short-term forecasts. The species feeds on bottom-dwelling prey, particularly crustaceans, and is often associated with hard bottom and reef habitats. Males create and defend nests in the summer. Fish reach maturity around two years old but can live as long as 13 years.

e. Question 1: Testing forecast skill

Forecast skill over the near-term derives from three sources: 1) initialization of the models with the current state of the world; 2) forecasts of environmental conditions, and 3) ecological processes. These factors contrast with long-term climate projections, which do not depend on appropriate initialization conditions because environmental forcing processes dominate.

We will test the forecast skill of dynamic range models by fitting them to historical data as described above ("Dynamic range models"), but using only data before year Y. We will examine Y from 1980 to 2004, so that we have 25 initialization years to test. We will then initialize the models with the observed species distribution in year Y, run the dynamic range models forward for 10 years, and compare the predicted species distribution shifts to those observed in the ecological surveys. We will quantify the skill of the forecasts using anomaly correlation coefficients (ACC), bias, and root mean square error (RMSE) for the species latitude centroid, latitude of the northern 95th percentile of abundance, and latitude of the southern 5th percentile of abundance.

The models require environmental forecasts to run forward, and we will examine two options. First, we will use observations and historical reconstructions of the environment so that we can isolate uncertainty from the ecological model. The bottom trawl surveys, regional oceanographic hindcasts (*13, 14*), and global ocean reanalysis products (*15*) provide temperature and oxygen data for this purpose.

A true ecological forecast, however, uses forecast environmental conditions. Therefore, we will also use forecasts from the GFDL CM2.1 decadal prediction system (*5*). This climate model has been initialized every year from 1965-2011 and forecast forward from the initialization year for 10 years into the future. This set of tests will therefore include both uncertain ecological dynamics and uncertain climate forcing. Because oceanographic forecasting in the Northeast U.S. is an active area of research, we will incorporate newer forecast products if they become available during the duration of this project (Jon Hare, pers. comm.).

We will compare skill from the dynamic range model against the forecasts from two simpler models. First, we will use a statistical habitat model (*1*). This model assumes that ecological dynamics like growth and dispersal are unimportant, and that species distributions are always in equilibrium with their habitat. This may be a reasonable assumption for fast-growing and highly mobile species like squid. Second, we will compare our forecasts against a persistence forecast, which is the assumption that species do not move from their initialized distribution.

f. Question 2: Times-scales of forecast skill

Forecast skill typically degrades with time. We will compare forecast skill using ACC, bias, and RMSE for each year from 1-10 years out from the initialization year for each species. We will compare the rate and magnitude of decline in skill relative to persistence and statistical habitat models. We will also compare the decline is skill when the environment is known vs. when the environmental conditions have also been forecast.

We will work with Brandon Muffley and other stakeholders to design appropriate communication methods for the forecasts and the forecast skills (e.g., maps, graphs, and tables). We will evaluate forecast skill and discuss how the degree of skill affects the use of forecasts in management decisions during our second annual meeting.

g. Question 3: Extensions to include fishing

Because all four case study species are the target of fisheries, interactions with fishing may be an important influence on species distributions. Fisheries can change species distributions by removing fish from particular geographic regions and causing a range contraction in that region, by impeding range expansion through fishing on the leading edge of a species range (*20*), or by reducing overall density and causing a density dependent range contraction towards high quality habitat (*21*). The availability of detailed catch location data in the Northeast U.S. allows us to test whether fishing has contributed to shifts in species distributions. We will extend the dynamic range model to include harvest effects as an additional term in the population dynamics model, then re-fit the models to the data. We will use commercial catch records from the NEFSC that quantify the location and amount of fisheries landings since 1977 in 10' grids (*22*). We will also add recreational catch for summer flounder, for which such catches are substantial. The data show that the location of fishing has changed through time, and may therefore be important in explaining shifts in species distribution and abundance. The relative contributions of fishing and temperature change to observed distribution and abundance changes will be extracted by simulating from the Bayesian posteriors either without fishing or with stable temperatures. We will use Bayes Factors and the Bayesian predictive information criterion (BPIC) to select from among models that do or do not include fishing (*23*).

If fishing is an important factor influencing species distributions, we will include projections of fishing effort in our near-term forecasts as well. We will work with MAFMC to identify which fishing scenarios should be included in these forecasts. In addition, we will have developed a tool for testing alternative management strategies in the context of a Management Strategy Evaluation (MSE). We expect this extension will be particularly relevant for summer flounder, for which the MAFMC is currently planning an ecosystem MSE. The influence of prospective fishing rates and spatial allocations could be tested in the dynamic range models to examine the consequences of different management choices.

We will present to and discuss the full project with the MAFMC members during a full Council meeting near the end of the project. The discussion will focus on use of the operational forecast system in decision-making, strengths and weaknesses of the forecast system, and the potential to expand the system in the future to other species.

Data Sources

- Bottom trawl surveys from federal and state waters will provide the historical information on the distribution and abundance of case study species. The federal data are publicly available through our OceanAdapt website (http://oceanadapt.rutgers.edu). My lab has data for the NEAMAP state water survey (Cape Cod, MA to Cape Hatteras, NC) through a data sharing agreement with the Virginia Institute of Marine Science. While not critical to project success, we will also set up data access agreements with Massachusetts, New Hampshire, and Maine state surveys.
- Historical oceanographic conditions (temperature and oxygen) are available from the bottom trawl surveys, from the freely shared Curchitser lab regional oceanographic model at Rutgers (*13*), and from the publicly available SODA oceanographic reanalysis (*15*).
- Historical forecasts of oceanographic conditions are publicly available as part of the Coupled Model Intercomparison Project 5 (CMIP5) for the GFDL CM2.1 model (*5*).
- Fisheries catch data for the Northeast U.S. are in hand in my lab through a partnership with the Northeast Fisheries Science Center (*22*).

Challenges

a. Potential scientific limitations to the proposed research and/or methods, and how the project design takes them into account.

One potential limitation is the uncertainty in currently available oceanographic forecasts (*5*). For example, uncertainty in oceanographic conditions limited the accuracy of stock assessment forecasts for yellowtail flounder (*24*). We will therefore also use historical observations to detect the extent to which more accurate climate forecasts would improve ecological forecasts. A next generation of climate forecasts is currently being developed for the

Northeast U.S., and so our ecological forecast system will be ready to use them when available. However, we may also learn that ecological forecast skill mostly depends on ecological processes and initialization state, in which case oceanographic forecast skill may be less important.

b. Potential barriers that may limit the project's usefulness to decision-making.

If we learn that forecast skill is very low, that may limit the utility of our forecasts for tactical decision-making. However, understanding uncertainty is a key step for appropriately incorporating information into decision-making, and fisheries managers are used to decision-making in a highly uncertain environment.

If we learn that ecological forecast skill depends on the availability of oceanographic forecasts, the lack of operational oceanographic forecasts for the Northeast U.S. would limit the deployment of our forecasting system in the short-term. However, operational forecasts are actively under development by NOAA and WHOI and are expected by project end.

Finally, the MAFMC (and other fisheries managers) are still learning how to use ecosystem context information in their fishery management decisions, and formal decision-making processes do not yet exist the way they do for stock assessment results. This project will be joint learning experience: the scientists will be learning how to produce the forecasts, while the managers will be learning how to use them. This learning process is a key reason for regular meetings and for the involvement of Brandon Muffley in the project team.

Consideration of Climate

This project explicitly addresses the impacts of climate change and climate variability on marine animals with the goal of producing better forecasts of those impacts to guide fisheries management and marine spatial planning.

References

1. J. W. Morley *et al.*, Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLOS ONE* **13**, e0196127 (2018).
2. Mid-Atlantic Fishery Management Council, "Ecosystem Approach to Fisheries Management Guidance Document" (2016).
3. D. Tommasi *et al.*, Managing living marine resources in a dynamic environment: the role of seasonal to decadal climate forecasts. *Prog. Oceanogr.* **152**, 15 (2017).
4. M. R. Payne *et al.*, Lessons from the First Generation of Marine Ecological Forecast Products. *Frontiers in Marine Science* **4**, (2017).
5. D. Tommasi *et al.*, Multi-Annual Climate Predictions for Fisheries: An Assessment of Skill of Sea Surface Temperature Forecasts for Large Marine Ecosystems. *Frontiers in Marine Science* **4**, 1 (2017).
6. M. C. Urban *et al.*, Improving the forecast for biodiversity under climate change. *Science* **353**, aad8466 (2016).
7. S. Gaichas *et al.*, "DRAFT Mid-Atlantic EAFM Risk Assessment: Documentation and Results" (Mid-Atlantic Fisheries Management Council, 2018).
8. MAFMC, 2014. http://www.mafmc.org/strategic-plan. Accessed September 11, 2014.
9. MAFMC, 2014. http://www.mafmc.org/workshop/2014/east-coast-climate-change-and-fisheries-governance-workshop. Accessed September 11, 2014.
10. J. Pagel, F. M. Schurr, Forecasting species ranges by statistical estimation of ecological niches and spatial population dynamics. *Global Ecol. Biogeogr.* **21**, 293 (2012).

11. J. W. Morley, R. D. Batt, M. L. Pinsky, Marine assemblages respond rapidly to winter climate variability. *Global Change Biol.* **23**, 2590 (2017).
12. M. L. Pinsky *et al.*, Dispersal provided resilience to range collapse in a marine mammal: insights from the past to inform conservation biology. *Mol. Ecol.* **19**, 2418 (2010).
13. S. Zhang, E. N. Curchitser, D. Kang, C. A. Stock, R. Dussin, Impacts of Mesoscale Eddies on the Vertical Nitrate Flux in the Gulf Stream Region. *Journal of Geophysical Research: Oceans* **123**, 497 (2018).
14. D. Kang, E. N. Curchitser, Gulf Stream eddy characteristics in a high-resolution ocean model. *Journal of Geophysical Research: Oceans* **118**, 4474 (2013).
15. J. A. Carton, G. A. Chepurin, L. Chen, SODA3: A New Ocean Climate Reanalysis. *J. Clim.* **31**, 6967 (2018).
16. M. L. Pinsky, M. Fogarty, Lagged social-ecological responses to climate and range shifts in fisheries. *Clim. Change* **115**, 883 (2012).
17. M. L. Pinsky, B. Worm, M. J. Fogarty, J. L. Sarmiento, S. A. Levin, Marine taxa track local climate velocities. *Science* **341**, 1239 (2013).
18. R. J. Bell, D. E. Richardson, J. A. Hare, P. D. Lynch, P. S. Fratantoni, Disentangling the effects of climate, abundance, and size on the distribution of marine fish: an example based on four stocks from the Northeast US shelf. *ICES J. Mar. Sci.* **72**, 1311 (2015).
19. D. B. Packer *et al.*, "Essential Fish Habitat Source Document: Summer Flounder, *Paralitchthys dentatus*, Life History and Habitat Characteristics. NOAA Tech. Memo. NMFS-NE-151" (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 1999).
20. E. Fuller, E. Brush, M. L. Pinsky, The persistence of populations facing climate shifts and harvest. *Ecosphere* **6**, 153 (2015).
21. A. D. MacCall, *Dynamic geographic of marine fish populations*. (University of Washington Press, Seattle, WA, 1990).
22. S. Chang, "Seasonal distribution patterns of commercial landings of 45 species off the Northeastern United States during 1977-88. NOAA Technical Memorandum NMFS-F/NEC-78" (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Science Center, 1990).
23. T. Ando, Bayesian predictive information criterion for the evaluation of hierarchical Bayesian and empirical Bayes models. *Biometrika* **94**, 443 (2007).
24. T. J. Miller, J. A. Hare, L. A. Alade, A state-space approach to incorporating environmental effects on recruitment in an age-structured assessment model with an application to Southern New England yellowtail flounder. *Can. J. Fish. Aquat. Sci.* **1270**, cjfas (2016).