Request for FY2015 Fisheries And The Environment Funds

The following information must be listed on the cover sheet:
1. Title: **Evaluating IPCC AR5 projected climate change impacts on Bering Sea (AK) fish and fisheries using a management strategy evaluation.**

2. Principal Investigator: **Anne Hollowed,**

3. Principal Investigator Institution: **NOAA/NMFS Alaska Fisheries Science Center**

4. Associated NMFS Fisheries Science Center (or Centers if PIs from other Centers are collaborating) **None**

5. Research Priority (#) for this Proposal (Select a FATE Research Priority listed below). **#5.**

6. Project Duration (1 or 2 years) **2 years**
7. Total Funding Request
8. Year 1 Request (all institutions)
9. Year 2 Request (all institutions, if applicable)
10. Lead NMFS Investigator (if the Principal Investigator is non-NMFS) N/A
11. Lead NMFS Investigator organization (Center/Division/Branch) See above
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20. List institutional breakdown of Year 2 budget (institution: funding request for year 2)

Background: Climate change is a global issue affecting marine ecosystems and species that span multiple international boundaries, and is one of the most universal challenges facing fisheries scientists and managers around the world. Even the most conservative Intergovernmental Panel on Climate Change (IPCC) models project significant increases in sea surface temperatures (SST) in most systems, particularly for arctic and subarctic systems where climate change is expected to have the strongest effects (IPCC 2014). Yet the effect of warming climate conditions on marine ecosystems and species may be system and species dependent, and exhibit considerable variation across space and time (IPCC 2014, Poloczanska et al. 2013, Cheung et al. 2011).

To address this challenge scientists have developed global climate and earth system models (CGM and ESM, respectively) to project future conditions. These models are being tested regionally and discussed globally in an effort to initiate an international collaboration to provide quantitative estimates of the status and trends of commercial fish and fisheries worldwide by 2019 (see review in Hollowed et al. 2014). In particular, fisheries and ecosystem modelling communities have developed a variety of different models ranging from minimally realistic single-species climate enhanced stock projection models (SS-CEM) with detailed treatment of process error, measurement error and model misspecification to whole ecosystem models with complex treatment of ecosystem interactions and only modest treatment of uncertainty (Table 1; Plagányi et al. 2011; Stock et al. 2011). Because there are strengths and weaknesses to each modelling approach, ideally a regional projection of the implications of climate change on fisheries would include the full range of modelling approaches (Hollowed et al. 2013). Yet, the proliferation of modelling improvements and global projections creates a dilemma for regional ocean modelers and fisheries scientists as the number of possible permutations that could be explored rapidly can become too large to manage. Identifying a reasonable range of representative futures (with sufficient contrast in scenarios) and biological models allows analysts to compare projections and report on the relationship between model complexity, efficiency, and the computational costs of increased ecological realism in models (Planque et al. 2011; Link et al. 2012). Given the rapid pace of improvements in global climate models, there is immediate need for modeling tools and frameworks that can downscale output from Global Climate Models (GCMs) for use in regional ocean simulations and fisheries models. Such advancement would ensure that fisheries models and management are keeping pace with rapidly evolving climate change projections.

The Eastern Bering Sea Case Study: This issue is at the forefront of climate change issues and NMFS fishery management in the Alaskan Eastern Bering Sea (EBS). The 2-4 ^{o}C projected increase in mean summer sea surface temperature is expected to alter the Bering Sea marine ecosystem through shifts in trophic demand, predator and prey distributions and overall system productivity (IPCC 2014, Hermann et al. *in review*), yet only a few authors have attempted to quantitatively estimate the magnitude of these impacts on future stock status and fishery yield. Multiple global and regional climate models predict increases in primary production associated with future climate conditions, and thus primary consumers, with strong bottom-up population controls, may increase biomass under warmer climate conditions (Hermann et al., 2013). For upper level consumers the effect of climate change is less clear since increased prey biomass does not always translate into increased production. Further, recent studies indicate that ecosystem dynamics can substantially influence optimal harvest strategies in multi-species fisheries (Kasperski 2014) and impact the cost of harvesting commercial species (Haynie and

Pfeiffer 2013), thus climate driven changes to predation and production could alter future optimal harvest strategies.

We propose a proof-of-concept implementation of a Management Strategy Evaluation (MSE) framework for evaluating the performance of resource management strategies under different climate change scenarios. We will apply the framework to several fish and invertebrate species from the EBS, for which changes in productivity have been linked to climate variability. We will evaluate the following questions with this work: 1) how will climate change impact the productivity (in terms of growth and recruitment) and survival (in terms of predation mortality) of key species?; 2) are current fishery management approaches robust to climate-driven changes or should additional alternative harvest control rules be used?; and 3) what is the expected change in future fishable biomass and recommended harvest rates under climate change? We will also test software for rapid uptake of GCM output into regional ocean circulation models as a demonstration project for the Bering Sea LME and develop and test a framework for evaluating climate change effects on fish and fisheries that will be of global interest.

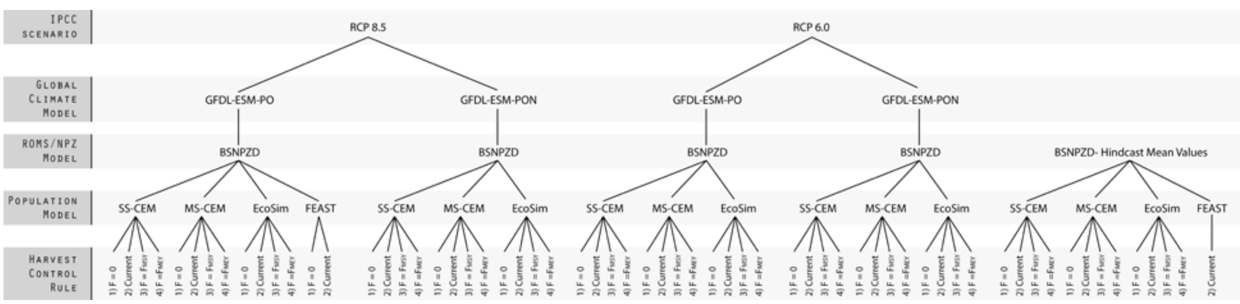

Figure 1. Diagram of proposed climate to ecosystem MSE framework.

Approach: Our ambitious project is achievable due to the coordination between multiple PIs that have already conducted the groundwork for this study. This proposed study represents an organized effort to couple existing models and tools in a comprehensive analysis to address the impact and uncertainty around one of the most pressing management issues facing fisheries in Alaska. Thus we will leverage model frameworks from a recently completed integrated research project (BEST-BSIERP) as well as results from FATE project 2014-05 to complete part of this project. That said, while we plan to utilize runs provided by FATE project 2014-05, the project proposed here is a new analysis and thus should not be considered a multi-year extension of a previously funded FATE project.

Year 1: Climate, ROMS, and NPZ modeling: We will utilize the existing Bering Sea 10K- coupled Regional Ocean Model System-Nutrient Phytoplankton Zooplankton Detritus model (BSNPZD; Hermann et al. in review) to project future ocean conditions in the EBS as a test case for this study (Fig. 1). The BSNPZD is a coupled biophysical ROMS-NPZD ocean model specifically designed for the Bering Sea lower trophic levels and has been extensively tested during the BEST-BSIERP project (Hermann et al. 2013). The ability of this model to replicate observed indices of the Bering Sea relevant to fisheries is being further tested in Phase 1 of FATE project 2014-05. Phase 2 of the FATE project 2014-05 includes funds to run projections driven by CIMIP 5 climate scenarios based on the GFDL Earth System Model (GDFL-ESM). The GFDL-ESM model represents a major breakthrough in computing, providing improved spatial resolution and the inclusion of biogeochemistry and thus was selected for the base GCM for this project.

The following regional ocean model scenarios will be used in this project: 1) two BSNPZD realizations (supplied from FATE 2014-05) where ROMS boundary conditions were forced with physics from RCP 8.5 (high) and 6.0 (moderate) scenarios of the GDFL-GCM (hereafter GDFL-ESM-PO); 2) two dynamically downscaled nutrient scenarios derived from the GFDL-ESM (RCP 8.5 and 6.0) to drive the boundary conditions of the BSNPZD (hereafter GFDL-ESM-PON; Fig. 1). Scenarios from other modeling centers or emissions scenarios may be considered if necessary, but to ensure the success of the project, we will first focus on using the GFDL-GCM and ESM models. We will utilize newly developed downscaling software packages (Kristiansen 2014) as well as software developed at PMEL by PI Hermann to interface the BSNPZD and the GFDL-ESM models.

Year 2: Management strategy evaluation of climate impacts on fish and fisheries: The impacts of projected future ocean conditions on commercially important fish (i.e., walleye pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*), arrowtooth flounder (*Atheresthes stomias*), and norther rock sole (*Lepidopsetta polyxystra*) and invertebrates (i.e., euphausiids and snow crab(*Chionoecetes opilio*) will be derived from implementing MSEs using 4 types of population dynamic models that range in ecological and statistical complexity (Fig. 1, Table 1): single species climate enhanced stock assessment models (SS-CEM), multispecies climate enhanced stock assessment models (MS-CEM), climate-driven food web models (EcoSIM), and a dynamic fully coupled spatially explicit gradient tracking ecosystem model (FEAST). These ecological models have been previously developed and tested for the EBS and are all currently operational (Ianelli et al., in review, Holsman et al. in review, Moffit et al. in review, Aydin et al. in review). The 4 types of climate-driven population dynamic models will be coupled with an economic model (e.g., Kasperski 2014) to evaluate climate effects on production and harvest on various targeted groundfish species (i.e., walleye pollock, Pacific cod, arrowtooth flounder) as well as other species in the system (e.g., forage fish, flatfish, crab). We aim to contrast the 4 biological models because each contains different complexity across statistical, trophic, and allometric scales.

> "***Scenarios*** are essentially a collective set of assumptions about possible futures, intended to give the decision-maker a strategy-planning framework. A ***projection*** is a prediction, usually limited to part of an overall system … that is based on a particular scenario or suite of scenarios" *Walsh et al. 2014*

The general approach will include 1) statistically fitting the population-dynamics models to historical survey and fishery biomass data in order to derive estimates of recruitment, historical harvest rates, selectivity, and annually varying natural mortality; 2) fit recruitment estimates from each model to spawning biomass and environmental covariates from the hindcast BSNPZD model (e.g., cold-pool area, bottom temperature, zooplankton biomass; see indicators described in FATE 2014-05 project), 3) use AIC to select the subset of climate indices that best fit each model specific recruitment, and 4) project the model forward in operating mode for each unique GFDL-ESM / climate scenario combination (Fig. 1). Here we adopt the definition of "scenario" and "projection" from Walsh et al. (2014; Box right). For the latter, in each future simulation year we will simulate recruitment (using n random draws from the recruitment model parameter estimates from the best AIC-selected or averaged models; n will depend on computing capacity).

In each simulation year, harvest rate will be set using a specified harvest control rule and "realized harvest" will be based on economic conditions and fisher behavior. These become inputs for the next year of the simulation. Specifically modeling the economics behind the expected realized harvest adds fisher behavior and economic realism to the analysis, which is vital when estimating future harvest for species such as arrowtooth flounder that are only rarely targeted and catches are frequently far below harvest limits. The economic and fisher behavior models will include the effects of socio-economic drivers such as input and output prices and species abundances (e.g., Kasperski 2014). Models used in this project, we will be informed by the results of models of spatial behavior of the fisheries (e.g., Haynie and Layton (2010), Haynie and Pfeiffer (2013)) and will draw on current recent analysis of the Amendment 80 fishery sector that targets arrowtooth flounder (Abbott et al. *forthcoming*). We plan to evaluate at least 4 harvest control-rules using the SS-CEM, MS-MCEM, and EcoSim models: 1) no fishing (F=0), 2) current harvest control rules (e.g., $F_{40\%}$ with a 2 million ton cap), 3) an alternative multi-species control rule such as sustainable yield (e.g., Holsman et al., *in review*) and 4) multi-species maximum economic yield (Kasperski, 2014). The computational complexity and cost of running FEAST limits the number of harvest scenarios that can be explored. For this demonstration project we will apply only the current groundfish harvest strategy (2.0 million t overall groundfish cap and include the current control rule for selected target stocks) under two climate scenarios (RCP 8.5, and mean historical conditions; Fig. 1 and Table 1), as well as a no-fishing scenario under RCP 8.5.

Performance of HCR, given model assumptions and climate conditions, will be evaluated for each unique HCR-climate projection (63 total). Performance metrics will include trends and variability in recruitment, growth, natural mortality, catch, and biological reference points (e.g., unfished biomass, fishing rate that corresponds to x% of unfished biomass, etc.) and changes in age structure (if applicable). Additional metrics of population viability, such as the probability of a population dropping below a biomass threshold, will also be developed and evaluated.

Table 1. Comparison of biological models and number of simulations

Fishery Model	Statistical complexity	Ecological complexity	# scenarios	# of HCR scenarios	# runs
SS-CEM	High	Low: Climate and trophic effects on recruitment, whole EBS, annual timestep	5	4: No fishing, cur. strategy, MSY, MEY	20
MS-CEM:	High	Med: 3 species, age structured, predation interactions, climate effects on recruitment, no movement, whole EBS, annual time step	5:	4: No fishing, cur. strategy, MSY, MEY	20
EcoSIM	Medium	Med-High: 10+ species, bottom up and top down, simple functional response, no movement, whole EBS, annual time step	5	4: No fishing, cur. strategy, MSY, MEY	20
FEAST	Low	High: 10+ species, size and age structured, bottom up and top down, movement, 10 km grid, <1 min time step	2	2: No fishing, cur. strategy	3

Benefits: This project specifically addresses FATE research priority #5 in that we **will develop, evaluate, and implement a framework to couple IPCC scenario-driven global climate models to fisheries population models and compare the performance of harvest control rules under future climate scenarios**. Results of this work will provide essential information for strategic NMFS management of fisheries under future climate conditions. This project will also address priorities 6 (feasibility and utility of incorporating climate indices into fisheries assessment model), 4 (examine potential effects of climate change and fishing on managed species), 3 (MSE that evaluates alternative harvest control rules given predicted climate conditions and investigate potential climate change induced shifts in biological reference points), and 1 (develop and evaluate analytical tools to investigate mechanisms driving interactions between fisheries and climate).

Completion of this project will be the first attempt to fully quantify the impacts of climate change on fish and fisheries in the Bering Sea. We anticipate various outputs from the work that are directly applicable to fisheries management in the Bering Sea and elsewhere, including 1) characterization of the magnitude and variability of future climate effects on the biomass and harvest of each species in the Bering sea, 2) an emergent framework for coupling IPCC scenario driven ROMS-NPZ models to multi-species fisheries and economics models for the purpose of evaluating climate, predation, and fishery interactions on marine species, and 3) evaluation of whether current fishery management approaches may be robust to climate-driven changes in species production. Additionally, these results will also directly inform the management strategy evaluation (MSE) step of the ongoing Integrated Ecosystem Assessment in Alaska (IEA) and the ecosystem considerations chapter of annual fisheries Stock Assessment reports (SAFE).

Because project personnel include NMFS managers and researchers working on climate change, fisheries economics, and multi-species/ ecosystem management, this project will provide a framework and candidate suite of representative environmental and fishing pathways that would be used in National Climate Assessments, the Intergovernmental Panel on Climate Change Assessment, and the Fish-Model Intercomparison Project (Fish-MIP; multiple PI are also involved in Fish-MIP). The international Fish-MIP effort is in its initial phases of implementation and therefore this FATE project would assist both the national and global modeling efforts.

Deliverables: Anticipated deliverables will include a project report, 2-3 peer-reviewed publications and two or more presentations on the framework for linking GCMs to fisheries models, model development, climate impacts on fisheries, and approaches for managing fisheries under future climate change. See above section for contribution of model outputs and results to ongoing global, national, and regional assessments. Additionally, representative future scenarios will be discussed and selected during a PICES / ICES sponsored workshop to be held in Princeton, NJ in August 2015. This project will help inform the cost and benefits of downscaling physics only, or physics and nutrients from GFDL-ESMs, differences in model projections given fishery model complexity, and information that will inform strategic planning for the effects of climate on fisheries.

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