NOAA Fisheries Climate Science Strategy Five Year Progress Report

Jay Peterson and Roger Griffis (Editors)

Contributing Authors

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Copies of this report may be obtained online at:

http://spo.nmfs.noaa.gov/tech-memos

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List of Acronyms

ACLIM - Alaska Climate Integrated Modeling project
AFSC - Alaska Fisheries Science Center
ADF&G - Alaska Department of Fish and Game
AMAP - Arctic Monitoring and Assessment Programme
AMAPPS - Atlantic Marine Assessment Programs for Protected Species
AMO - Atlantic Multi-decadal Oscillation
AOML - Atlantic Oceanographic and Meteorological Laboratory
ASMFC - Atlantic States Marine Fisheries Commission
BASIS - Bering Arctic Subarctic Integrative Survey
BO - Biological Opinion
BOEM - Bureau of Ocean Energy Management
BRP - Biological Reference Point
BSEE - Bureau of Safety and Environmental Enforcement
CalCOFI - California Cooperative Fisheries Investigations
CBP - Chesapeake Bay Program
CC - California Current
CCE - California Current Ecosystem
CCIEA - California Current Integrated Ecosystem Assessment
CCLME - California Current Large Marine Ecosystem
CCS ROMS - California Current Regional Ocean Modeling System
CeNCOOS - Central and Northern California Ocean Observing System
CFI - Climate and Fisheries Initiative
CHaMP - Columbia Habitat Monitoring Program
CMIP5 - Coupled Model Intercomparison Project (Fifth phase)
CMIP6 - Coupled Model Intercomparison Project (Sixth phase)
CNMI - Commonwealth of the Northern Mariana Islands
COCA - Coastal and Ocean Climate Applications
CPS - Coastal Pelagic Species
CPUE - Catch Per Unit Effort
CTD - Conductivity Temperature Depth
CVA - Climate Vulnerability Assessment
CVTEMP - Central Valley Temperature Mapping and Prediction
DFO - Fisheries and Oceans Canada
DFW - Department of Fish and Wildlife
DisMAP - Distribution Mapping and Analysis Portal
EBFM - Ecosystem Based Fisheries Management
EBM - Ecosystem Based Management
EBS - Eastern Bering Sea
ECCWO - Effects of Climate Change on the World's Oceans
EcoCast - Ecological Forecast
EFH - Essential Fish Habitat

ENSO - El Niño - Southern Oscillation
ERDDAP - Environmental Research Division Data Access Portal
ESA - Endangered Species Act
ESP - Ecosystem and Socioeconomic Profile
ESR - Ecosystem Status Report
ESU - Evolutionarily Significant Unit
FEP - Fishery Ecosystem Plan
FMP - Fishery Management Plan
FTE - Full-time equivalent. Denotes a full-time federal employee.
GAM(s) - General Additive Model(s)
GARFO - Greater Atlantic Regional Fisheries Office
GCM(s) - Global Climate Model(s)
GEO - Gulf Ecosystem Observatory
GFDL - Geophysical Fluid Dynamics Laboratory
GOA RAP - Gulf of Alaska Regional Action Plan
GoMMAPPS - Gulf of Mexico Marine Assessment Programs for Protected Species
GMRAP - Gulf of Mexico Regional Action Plan
GRNMS - Gray's Reef National Marine Sanctuary
GWA - Gulf Watch Alaska
HAB - Harmful Algal Bloom
HMS - Highly Migratory Species
IBM - Individual-Based Model
ICCAT - International Commission for the Conservation of Atlantic Tunas
ICE-FM - Incorporating Climate and Environmental Information into Fisheries Management
ICES - International Council for the Exploration of the Sea
IEA - Integrated Ecosystem Assessment
IMBeR - Integrated Marine Biosphere Research
IOC - Intergovernmental Oceanographic Commission of UNESCO
IOOS - Integrated Ocean Observing System
IPCC - Intergovernmental Panel on Climate Change
ISEMP - Integrated Status and Effectiveness Monitoring Program
JISAO - Joint Institute for the Study of the Atmosphere and Ocean
JSOES - Juvenile Salmon and Ocean Ecosystem Survey
J-SCOPE - JISAO Seasonal Coastal Ocean Prediction of the Ecosystem
LCA - Loggerhead Conservation Area
LK/TK - Local Knowledge/Traditional Knowledge
LMR - Living Marine Resource
LOSI - Loss of Sea Ice
LST - Land Surface Temperature
LTER - Long- Term Ecological Research
MACE - Midwater Assessment and Conservation Engineering
MAPP - Modeling, Analysis, Prediction and Projection
MHW - Marine Heatwave
MICE - Model of Intermediate Complexity for Ecosystem Assessment

MOM6 - Modular Ocean Model 6
MOM-TOPAZ - Modular Ocean Model - Tracers in the Ocean with Allometric Zooplankton
MSE - Management Strategy Evaluation
NANOOS - Northwest Association of Networked Ocean Observing Systems
NAO - North Atlantic Oscillation
NASA MODIS - NASA Moderate Resolution Imaging Spectroradiometer
NBS - Northern Bering Sea
NCBO - NOAA Chesapeake Bay Office
NCC - Northern California Current
NCLIM - Northeast Climate Integrated Modeling
NCSS - NOAA Fisheries Climate Science Strategy
NCTC - National Conservation Training Center
NEFSC - Northeast Fisheries Science Center
NEPA - National Environmental Policy Act
NERAP - Northeast Regional Action Plan
NGO - Nongovernmental Organization
NHD - National Hydrography Dataset
NMFS or NOAA Fisheries - National Marine Fisheries Service
NOAA - National Oceanic and Atmospheric Administration
NOAA/CPO - NOAA Climate Program Office
NOAA DisMAP - NOAA Distribution Mapping and Analysis Portal
NOAA NESDIS - NOAA National Environmental Satellite, Data, and Information Service
NOFO - Notice of Funding Opportunity
NOS - National Ocean Service
NPFMC - North Pacific Fishery Management Council
NWFSC - Northwest Fisheries Science Center
OA - Ocean Acifidification
OAR - Office of Oceanic and Atmospheric Research – Also called NOAA Research
OST - Office of Science and Technology
PacFIN - Pacific Fisheries Information Network
PAM - Passive Acoustic Monitoring
PEEC - Preview of Ecosystem and Economic Conditions
PFMC - Pacific Fisheries Management Council
PICES - North Pacific Marine Science Organization
PIFSC - Pacific Islands Fisheries Science Center
PIRAP - Pacific Islands Regional Action Plan
PIRO - Pacific Islands Regional Office
PIT - Passive Integrated Transponder
PIVA - Pacific Islands Vulnerability Assessment
PMEL - Pacific Marine Environmental Laboratory
PRD - Protected Resources Division
PSTAT - Pacific Sablefish Transboundary Assessment Team
RACE - Resource Assessment and Conservation Engineering
RAMP - California Risk Assessment and Mitigation Program

RAP - Regional Action Plan
RCPs - Representative Concentration Pathways
ROMS - Regional Ocean Modeling System
RREAS - Rockfish Recruitment and Ecosystem Assessment Survey
S-RAP - SEUSCS Regional Action Plan
S2A - Seasonal to Annual
S2S - Sub-seasonal to Seasonal
SAFE - Stock Assessment and Fishery Evaluation
SAIP - Stock Assessment Improvement Plan
SBS - Southern Bering Sea
SCCOOS - Southern California Coastal Ocean Observing System
SCOAR - Scripps Coupled Ocean-Atmosphere Regional modeling system
SCTLD - Stony Coral Tissue Loss Disease
SDM - Spatial Distribution Model
SEFSC - Southeast Fisheries Science Center
SERO - Southeast Regional Office
SEUSCS - Southeast United States Continental Shelf
SHRU - Salmon Habitat Recovery Units
SHSTM - Salmon Habitat Status and Trends Monitoring
SLR - Sea Level Rise
SRKW - Southern Resident Killer Whales
SSC - Scientific and Statistical Committee
SSP - Shared Socio-economic Pathway
SST - Sea Surface Temperature
SWFSC - Southwest Fisheries Science Center
SWFSC-UCSC and SWFSC/UCSC – SWFSC-University of California Santa Cruz
TMGC - Transboundary Management Guidance Committee
TOTAL - Temperature Observations to Avoid Loggerheads
UAS - Uncrewed Aircraft Systems
UAV - Unmanned Aerial Vehicle
UME - Unusual Mortality Events
USFWS - United States Fish and Wildlife Service
USGS HUC4 - Hydrologic Unit Code 4, a geographic sub-basin
USN - United States Navy
VAST - Vector Autoregressive Spatio-Temporal
VIIRS - Visible Infrared Imaging Radiometer Suite
WCOFS - West Coast Operational Forecast System
WCRO - West Coast Regional Office
WGNARS - Working Group on the Northwest Atlantic Regional Sea
WRAP - Western Regional Action Plan

Executive Summary

The NOAA Fisheries Climate Science Strategy (NCSS)[1] was published in 2015 to increase the production, delivery, and use of the climate-related information needed to fulfill the agency's mandates in a changing climate. The NCSS identifies a suite of objectives and specific actions to help achieve this goal. The NCSS objectives focus on supporting infrastructure, tracking change, understanding mechanisms, projecting future conditions, and informing and supporting management. Beginning in 2016, NOAA Fisheries worked with partners in each region to develop seven Regional Action Plans (RAPs) to implement the NCSS over a 3-5 year period. In 2020, NOAA Fisheries conducted an assessment of progress to implement the NCSS over the five years since the release of the NCSS.

This five year progress report highlights the goals, activities, and accomplishments of the seven RAPs and national efforts from 2016-2020. Chapters are devoted to each RAP and provide summaries of the progress made to date. The chapters also provide recommendations for future focus areas and actions for continued progress towards achieving the NCSS objectives in each region.

Each region has a unique set of capabilities and challenges for managing the Nation's living marine resources under changing climate and ocean conditions. The individual RAP chapters herein provide the most appropriate and complete description of regional progress to implement the NCSS. Overall, a number of the priority goals listed in the NCSS have been met, while progress towards many continues, and others are in clear need of additional effort. A few trends in the types of activities and path to success are:

- Many activities and a majority of the progress overall tended to be associated with NCSS objectives related to maintaining infrastructure and tracking changes to provide early warnings. Products and tools such as Ecosystem Status Reports (ESRs) and Climate Vulnerability Assessments (CVAs) have been, or are nearly, developed in each region.
- Good progress was made on actions affiliated with the NCSS objectives focused on understanding mechanisms and projecting future conditions. There was a bit more regional variability in terms of effort and progress towards achieving these objectives.
- There has been some progress to improve the science and tools to help support climate-informed resource management. Increased effort is needed to fulfill the NCSS objectives focused on developing and evaluating management strategies robust to changing climate and ocean conditions.
- In general, the areas of progress and the amount of progress align with the availability of science information and/or technical capability, the support of RAP activities by regional leadership, and available funding from regional and national programs.

[1] https://www.fisheries.noaa.gov/national/climate/noaa-fisheries-climate-science-strategy

- Establishment of NMFS Regional Climate Teams and RAPs has provided a framework that helped increase coordination, collaboration, and implementation of regional efforts to fulfill national goals.

While the many achievements and continued progress towards implementing the NCSS over the last five years should be celebrated, there is much still to be done to fulfill the NCSS and build a climate-ready NOAA Fisheries. A number of the NCSS recommended actions still need to be completed. Several of these recommendations are highlighted below within three categories of the NCSS objectives:

Support Essential Infrastructure and Track Change
- Rebuild and expand ecosystem surveys to fill in spatial and temporal gaps, and account for current and anticipated shifts in species distributions
- Work with partners to leverage capacity and resources
- Produce regular (e.g., annual) updates of Ecosystem Status Reports in each region
- Ensure adequate resources are dedicated to climate-related, process-oriented research to better understand, prepare for, and respond to future impacts

Understand Mechanisms of Climate Impacts and Project Future Conditions
- Identify regional data gaps and devise data collection and research programs to fill biological, physical, and socio-economic information needs
- Advance regional ocean, biogeochemical, ecosystem, and living marine resource models and model coupling
- Develop centralized databases and web tools to provide easy access to ecosystem and fisheries information, including species distribution shifts, ecosystem indicators, and stock status

Inform and Support Climate-Informed Management
- Establish climate-smart terms of reference for incorporating climate and ecosystem information into management and policy areas (e.g., fishery management and ecosystem plans, permitting, recovery plans, etc.)
- Work with fishery management councils to identify future climate and ecosystem scenarios (Scenario Planning) and evaluate risks and risk policies
- Operationalize management strategy evaluation frameworks. This includes working with fishery management councils to identify their needs and identifying strategies robust to anticipated climate, ecosystem, and socio-economic conditions
- Deliver Ecosystem Status Reports to fishery management councils and stakeholders on an annual basis to provide context and early warnings regarding ecosystem conditions
- Account for changing productivity and distribution within climate-smart biological reference points (BRPs) and develop “on-ramps” for incorporating climate information into living marine resource management

In summary, establishment and implementation of the RAPs has helped increase the coordination and execution of climate-related efforts called for in the NCSS. While progress has been made in some areas, meeting the NCSS goals will require enhanced resources to support data collection and management efforts, IT infrastructure and modeling capacity, and fostering strong communication between scientists, managers, and stakeholders. Working together to support and address climate science and management needs will allow NOAA Fisheries to better meet its stewardship responsibility for the Nation’s living marine resources.

1. Introduction

In 2014, NOAA Fisheries launched development of a comprehensive strategy to address the high and growing demand for information and tools to address the impacts of changing climate and ocean conditions on the nation's living marine resources (LMRs) and the communities that depend on them. The strategy built on previous efforts to assess climate impacts on LMRs and NOAA Fisheries' mission (Osgood, 2008), and identified needs for more information and science-based approaches to sustain LMRs and resource-dependent communities in a changing climate. Following extensive internal and external input, NOAA Fisheries published the NOAA Fisheries Climate Science Strategy (NCSS) in 2015 to increase the production, delivery, and use of climate-related information in fulfilling the agency's mission mandates (Link et al., 2015; Busch et al., 2016).

The NCSS was developed to guide efforts by NOAA Fisheries and partners to better understand, forecast, and respond to climate change impacts on LMRs and dependent communities. The NCSS identifies seven key objectives (Figure 1.1) to meet key information requirements on what is changing, why it is changing, how it will change in the future, and how best to respond. The NCSS was designed to be both national in scope and regionally-focused, and customized and implemented through Regional Action Plans (RAPs) that address the specific climate impacts, science capabilities and resource management needs in each region.

Following publication of the NCSS, NOAA Fisheries established regional teams to develop and guide implementation of the RAPs in each region over a 3-5 year period. The regional teams consisted of personnel from NOAA Fisheries science centers and regional offices. Throughout the RAP development process, the teams worked with regional partners to identify science and management needs and actions to implement the NCSS in each region with available resources. Soon after the publication of the NCSS, NOAA Fisheries released a national level Ecosystem-Based Fisheries Management (EBFM) Policy in 2016. The NCSS and EBFM Policy provide a synergistic approach to managing living marine resources and their ecosystems, and highlight the importance of considering the ecosystem as a whole, including changing climate and ocean conditions, when making LMR management decisions.

The year 2020 marked five years since the release of the NCSS and an initial waypoint to assess progress and needed actions to implement the NCSS via national and regional activities. In 2020, RAP teams worked with the Office of Science and Technology to conduct assessments of progress towards meeting the NCSS objectives and regional priorities, and to identify priority gaps and needs for future actions. This document summarizes those assessments of progress to implement the NCSS and RAPs over the last five years. It also highlights some of the many priority needs and proposed solutions to help guide future RAPs.

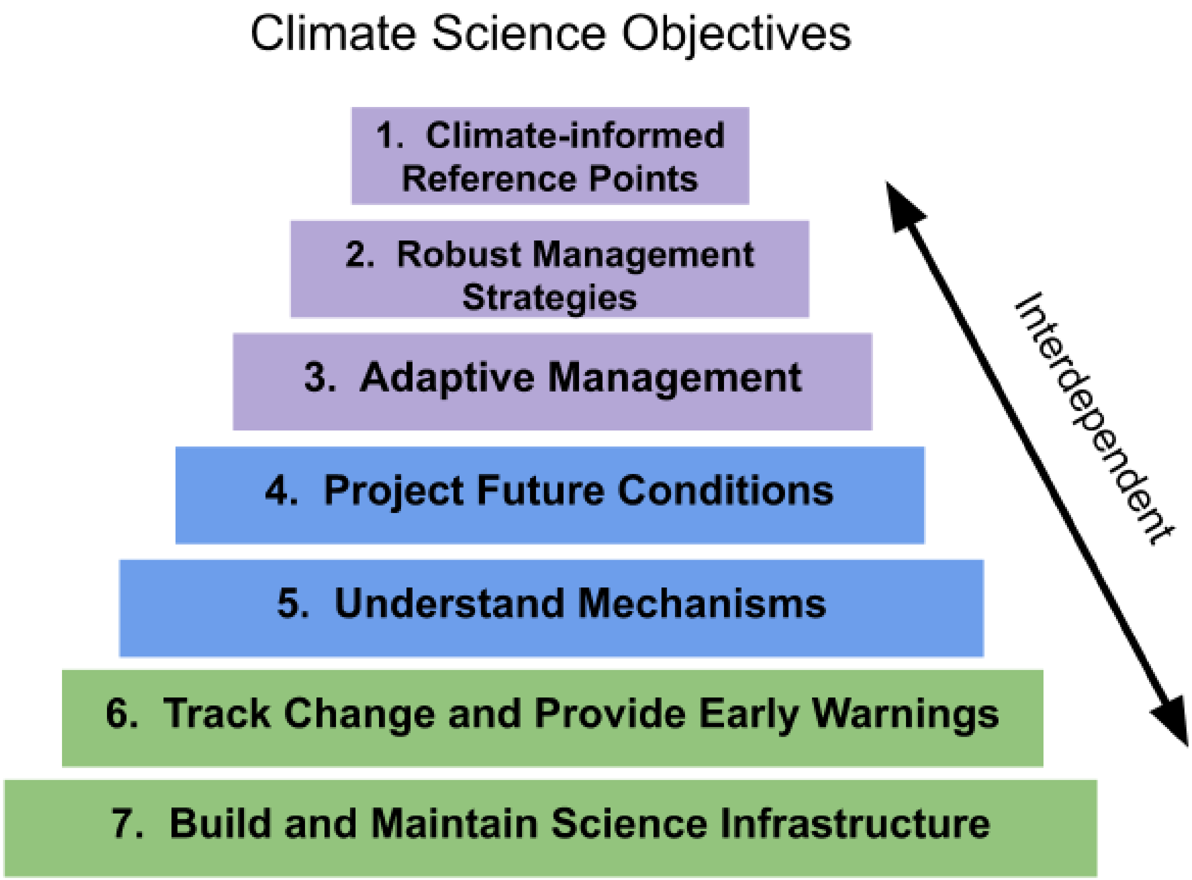

Figure 1.1. Pyramid of the seven main objectives of the NOAA Fisheries Climate Science Strategy (Link et al., 2015).

2. National

2.1 Introduction

Much of the focus in implementing the NCSS centers around a regional approach; addressing locally specific climate impacts and information needs and building regional capacity and partnerships to address goals under each of the seven main NCSS objectives (Figure 1.1). Though each region has specific science and management goals and capacities, there are a number of actions that address needs in all regions and are able to be addressed by taking a more national approach. Unlike the Regional Action Plans, there was not a specific "National Action Plan" developed and published in the same manner. Rather, a variety of priority or recommended actions in the NCSS lend themselves to national level efforts, and goals and metrics to accompany these were developed internally. National Offices and Programs also directly (e.g., funding) or indirectly supported the RAP efforts. The following sections present a synthesis of the national-level goals, activities, and achievements organized under each of the seven main objectives. The seven objectives are organized into a pyramid in order to depict that each objective supports those above it, and that climate-readiness depends on an integrated suite of capabilities from production of information and climate-informed advice, to effective use of that information in decision making. As such, the goals and activities will be described from the bottom to the top in numerically descending order of objectives.

2.2 Activities and Progress

Build and Maintain Infrastructure (Objective 7)

NOAA Fisheries is a service-based organization responsible for the stewardship of the nation's ocean resources and their habitats. U.S. fisheries are among the largest and most sustainable in the world, due in large part to a science and ecosystem-based approach to management. NOAA Fisheries depends on its network of five regional offices, six science centers, and more than 20 laboratories across the U.S. and its territories to provide high quality advice to resource managers. However, the NCSS identified a clear need for increased capacity to better understand changing climate and ocean conditions and their impacts on the nation's valuable living marine resources. Fulfilling this need requires a multi-pronged approach, including identifying and filling workforce, observational, and data gaps; better coordinating new and existing programs; and fostering and expanding the many valuable collaborations NOAA has with international, state, and local partners.

Goal(s)
Several specific goals were identified to help identify needs and actions and to build capacity to conduct climate-related research:

1. Complete and begin implementing NCSS RAPs in six regions by 2018

2. Maintain a nationally coordinated group of regional teams to promote and support climate activities within and across regions
3. Increase capacity for conducting management strategy evaluations (MSEs) in six regions by 2020, specifically through having a dedicated person in each region
4. Expand engagement with international partners

Activities – highlights
A number of actions to reach the goals were conducted over the past five years. Highlights of several are listed below.

- RAP teams were established soon after the 2015 publication of the NCSS. The teams worked with regional partners to develop, publish, and begin implementing seven RAPs, including five in 2016 (Bering Sea, Gulf of Mexico, Northeast, Pacific Islands, West Coast), one in 2018 (Gulf of Alaska) and one in 2020 (South Atlantic). Additional details are provided in each of the regional sections of this report.
- "Climate Quarterly" meetings - Along with the establishment of RAP teams, there has been a coordinated effort to hold quarterly teleconferences with people conducting climate-related activities across the regions. There are currently about 60 individuals from across the Science Centers, Regional Offices, and NOAA Fisheries headquarters offices that are invited to share information on recent and upcoming climate-related activities. More formally, the RAP teams develop annual progress reports that are presented to regional leadership as well as to the NOAA Fisheries Science Board to provide continued awareness of accomplishments and needs.
- MSE capacity - Dedicated funding has allowed each Center to hire a full-time employee for MSE development and build capacity in their region.
- International partners - A new framework between NOAA Fisheries and Fisheries and Oceans Canada was established to increase collaboration to understand and respond to climate impacts on fisheries (2019). Additionally, NOAA Fisheries, along with many international partners, hosted and co-organized the 4th International Symposium on the Effects of Climate Change on the World's Oceans[2] (2018).

Progress summary
Overall, there was great progress made in achieving the stated goals. Establishment of NMFS Regional Climate Teams and RAPs provided a positive framework that helped increase coordination, collaboration, and implementation of regional efforts towards national goals. Individual RAPs have been developed for seven regions and there is an active community of researchers in each region conducting climate-related research and other activities to address their specific needs. However, there is continued need to increase research capacity. Collaborations with federal, state, local, and international partners have helped increase this capacity, but it has not yet caught up with the demand for information needed by decision-makers.

Tracking Change (Objective 6)

NOAA Fisheries' world-class science-based enterprise is dedicated to the collection of environmental and fisheries information used to produce data-based assessments of fish stocks

[2] https://meetings.pices.int/meetings/international/2018/climate-change/background

and status of other living marine resources. In many cases, however, climate and environmental information is not explicitly incorporated into the assessments. Outside of direct incorporation in stock assessments, reports of ecosystem status and trends can provide important environmental context for managers when making decisions, can provide early warnings of improving or declining conditions, and provide commonly needed climate-related data inputs for species and ecosystem models.

Goal(s)
Specific goals to better track and report on changes to climate and ocean conditions include:
1. Establish and strengthen Ecosystem Status Reports (ESRs) in 6 regions by 2020
2. Annually track and report on the distribution of major fish stocks in each region

Activities – highlights
- Ecosystem Status - Through support from NOAA's Integrated Ecosystem Assessment (IEA) program, many regions have produced an Ecosystem Status Report (ESR)[3] or State of the Ecosystem report. The ESRs use a suite of indicators (e.g., physical, biological, human dimension) to provide decision-makers with information on past and current ecosystem conditions. They are produced for resource managers and stakeholders such as the Fishery Management Councils, National Marine Sanctuaries, state governments, and other marine resource management organizations. ESR production has increased over time and ESRs are produced in all five NOAA IEA program regions (Figure 2.1), some annually and others on longer timescales ranging up to every four years. Examples of regional reports and publication years are as follows: California Current (2016 - present); Gulf of Mexico (2013, 2017) and Florida Keys National Marine Sanctuary (2019); Northeast U.S. shelf (2002, 2009, 2011, 2018-present; includes Mid-Atlantic); West Hawai'i (2016, 2019); Alaska (1999 - present; sub-regions separated out starting in 2016 to now include Eastern Bering Sea, Gulf of Alaska, and Aleutian Islands).
- Marine Ecosystem Indicators Portal - A national marine ecosytem status web portal (https://ecowatch.noaa.gov) was developed to provide stakeholders with easy access to data and information to track changes in their marine ecosystems.

[3] IEA program webpage with links to the ecosystem status reports - https://www.integratedecosystemassessment.noaa.gov/national/Ecosystem-Status-Reports

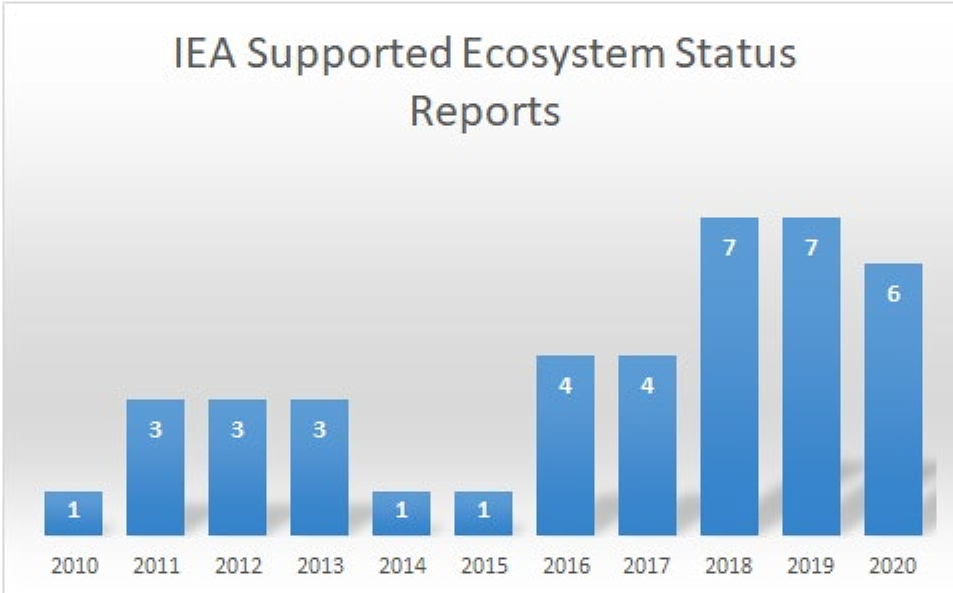

Figure 2.1. IEA supported Ecosystem Status Reports in five IEA program regions. Different regions produce ESRs on different timescales, from annually to every four years. 2020 was still in progress when this figure was created.

- Tracking species distributions - In 2014, Rutgers University and NOAA Fisheries launched the OceanAdapt website and database to provide information on the distribution of marine species in U.S. waters. The site was specifically designed as a tool to provide decision-makers, educators and others with information on past, current, and possible future changes in distribution of fisheries-related species based on fish survey data from NOAA Fisheries and other sources. Since the initial launch, the partnership has updated the site annually with new information from NOAA trawl survey data. The dataset was recently expanded to include historic data on fish stock distributions in some Canadian waters through collaboration with Fisheries and Oceans Canada.

Progress summary

Focused efforts have helped to establish ESRs in five new regions/sub-regions since 2015 while also expanding data collection, synthesis, and reporting and increasing the frequency of reporting of some previously established regional ESRs. There are currently ESRs available for eight regions/sub-regions, with many updated annually (NOAA, 2021). Following a national workshop in 2017, additional effort has been put into developing more automated procedures for some of the time-consuming operations that are performed in all regions, such as assembling data and plotting indicator trends. Two fishery management councils (NEFMC, NPFMC) request annual updates on ecosystem status and incorporate the information provided by the ESRs.

Tools such as OceanAdapt (https://oceanadapt.rutgers.edu) have proven to be quite valuable in terms of being able to visually show trends in the spatial distribution of fish stocks. Several fishery management councils have expressed the need to better understand current and future species distributions so as to have better information for addressing allocation concerns as species move across management jurisdictions.

Understanding Mechanisms (Objective 5)

Species, ecosystems, habitats, and human systems are affected by climate related changes in both positive and negative ways. Having a mechanistic understanding of how and why these different components are affected provides a basis for being able to assess vulnerability, risk, and adaptive capacity. Developing this mechanistic understanding requires process-based research that requires capacity and investment. Strong partnerships with research institutions and other NOAA Line Offices are critical to being able to leverage expertise and resources and make substantial progress. Resulting information and tools such as vulnerability assessments provide key information to help prioritize where additional science is needed and where management efforts may need to be focused.

Goal(s)

Several goals were identified to help better understand mechanisms and develop products to convey vulnerability of LMRs to changing climate and ocean conditions.

1. Advance understanding of climate-related impacts on fish stocks and fisheries
2. Complete fish climate vulnerability assessments (CVAs) in 6 regions by 2020
3. Complete Protected Species CVA for marine mammals and sea turtles by 2020

Activities – highlights

- COCA-NOAA Fisheries partnership[4] - NOAA Fisheries has partnered with the NOAA Research Climate Program Office through their Coastal and Ocean Climate Applications (COCA) program to fund research on the impacts of climate on fisheries and fishery-dependent communities. This has been a valuable partnership, with the majority of the funding for the program provided by NOAA Research but focused on addressing NOAA Fisheries needs. The program releases a notice of funding opportunity (NOFO) every 2-3 years. The initial NOFO (FY15) focused on funding research to better understand mechanisms of climate impacts on fisheries in the NE region and the impact on fishery-dependent communities. The next competition (FY17) included the NE/Mid-Atlantic and California Current. In FY19 the focus was on resilience of NE fishing communities. The most recent NOFO (FY20) included the NE, California Current, Bering Sea, and Gulf of Alaska.
- Vulnerability Assessments[5] (fish stocks, habitats, protected resources including mammals, turtles) - NOAA Fisheries completed the methodology for assessing the climate vulnerability of fish stocks in 2015 and committed to completing fish stock climate vulnerability assessments in at least six regions by 2020. The first fish stock climate vulnerability assessment was completed in the Northeast region in 2016. Similar assessments have been completed in five other regions (Southeast, Gulf of Mexico, Bering Sea, West Coast, Pacific Islands). In 2019 NOAA Fisheries completed the methodology for conducting climate vulnerability assessments for marine mammals. Since then marine mammal vulnerability assessments have been completed for the U.S.

[4] The COCA program was rebranded in 2021 to the Climate and Fisheries Adaptation (CAFA) Program. https://cpo.noaa.gov/CAFA

[5] NOAA Fisheries Climate Vulnerability Assessment web page - https://www.fisheries.noaa.gov/national/climate/climate-vulnerability-assessments

Atlantic and Pacific Coasts. Similarly, NOAA Fisheries completed methodologies for climate vulnerability assessments for sea turtles and habitats, and these assessments are on-going.

Progress summary
The COCA-NOAA Fisheries joint program has funded a modest number of projects in several regions (Figure 2.2). The seven projects funded in 2015 focused on climate impacts on fisheries in the Northeast. In 2017, five projects were funded across the California Current and Northeast. In FY19 there were five projects funded focused on resilience of Northeast fishing communities. The most recent set of projects, funded in FY20, consist of five projects that focus on developing integrated modeling frameworks to evaluate management strategies under different climate and ocean scenarios and inform climate-resilient fisheries management. Details of these projects are available through the program website (https://cpo.noaa.gov/CAFA).

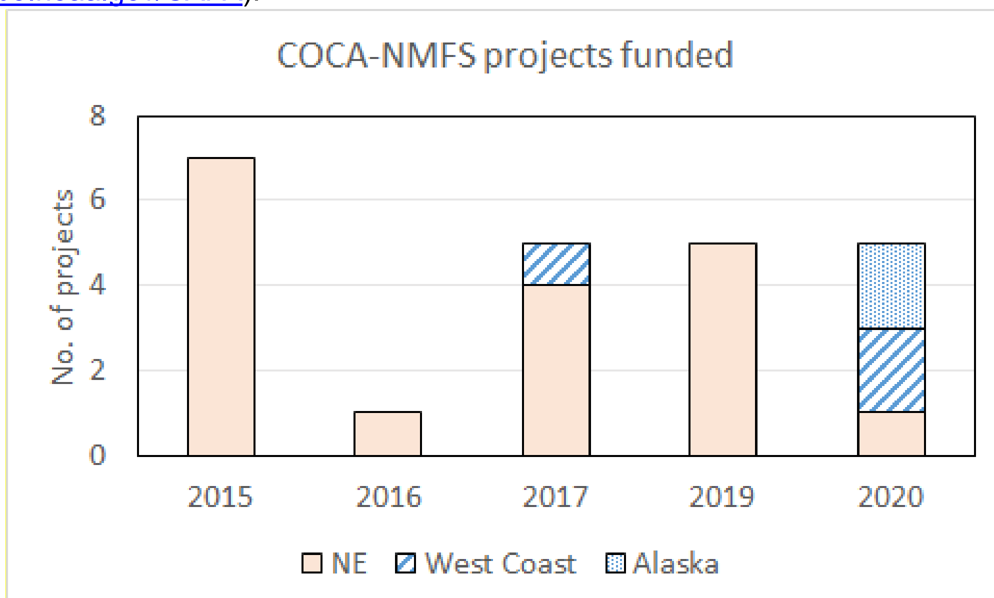

Figure 2.2. Projects funded by the COCA-NOAA Fisheries joint program focused on advancing the understanding of climate-related impacts on fisheries and fishery-dependent communities.

Since 2015, NOAA Fisheries has developed methodologies to assess climate vulnerability for fish stocks, marine mammals, sea turtles, and habitats. NOAA Fisheries achieved the goal of completing fish stock climate vulnerability assessments in at least six regions, completed climate vulnerability assessments for marine mammals in both the Atlantic and Pacific regions, and is on track to complete climate vulnerability assessments for sea turtles and habitats by 2022.

Projecting Future Conditions (Objective 4)

Forward-looking management of LMRs depends upon robust projections of future ocean conditions and the response of species, ecosystems and socio-economic components. Developing these model-based projections and responses is a major challenge, particularly when needing to down-scale to appropriate temporal and spatial scales relevant to management. Further, coupling across models to develop an integrated system that links physiochemical systems to marine resources and human communities and economies is not trivial. At a national level, efforts have been focused on developing partnerships and increasing resources to address model development and forecasting needs.

Goal(s)

1. Increase research focused on improving near-term forecasts and long-term projections
2. Identify gaps in needed information and capacity to project future climate and ocean conditions

Activities – highlights

- MAPP-NOAA Fisheries partnership[6] - The Climate Program Office Modeling, Analysis, Prediction and Projection (MAPP) Program partnered with NOAA Fisheries Office of Science and Technology to fund research focused on improving the modeling of climate impacts on the predictability of fisheries and other living marine resources across a variety of time-scales. In FY17 the partnership funded eight projects under the Marine Prediction Task Force and in FY20 another 12 projects were funded under the Marine Ecosystem Task Force.
- Climate and Fisheries Initiative[7] - Leadership from NOAA Research and NOAA Fisheries launched this initiative in early 2019 to develop recommended actions to address the NOAA Fisheries requirements for climate information under two timeframes: 1) near-term (near-real-time to decadal) and 2) longer-term (multi-decadal). Two expert teams developed a white-paper, finalized in April 2020, to report findings from the initiative. The white-paper outlines four specific actions to achieve the strategic vision of the initiative: 1) better utilize existing climate information, 2) advance NOAA's regional modeling system, 3) establish communities of practice and regional teams, and 4) fuel innovation through targeted research. The next step is the development of an implementation plan for the recommended actions.

Progress summary

Valuable partnerships with NOAA Research have provided resources to advance global and regional climate predictions and projections. Improvements to modeling capabilities, as well as the development of applications and tools relevant to decision makers' needs, continues to help advance our ability to be proactive in addressing climate impacts on fisheries.

Informing management (Objectives 1 - 3)

The top three levels in the Objective pyramid (Figure 1.1) focus on using science to create robust and flexible climate informed fisheries management advice. Integrating the science into the management process relies on an adaptive approach that includes close coordination between scientists and managers to better understand how climate variability influences

[6] MAPP Program website - https://cpo.noaa.gov/Meet-the-Divisions/Earth-System-Science-and-Modeling/MAPP/MAPP-Task-Forces/Marine-Ecosystem-Task-Force
[7] NOAA Climate and Fisheries Initiative website - https://www.fisheries.noaa.gov/topic/climate-change#noaa-climate-and-fisheries-initiative

uncertainty, and to identify options for incorporating climate information. Options, including alternative management approaches and strategies, need to be considered and evaluated. The best management approaches for LMRs today may not be the best management practices in the future, and thus having the capability and desire to evaluate various strategies under future conditions will help determine the most robust course of action to pursue.

Goal(s)

1. Coordinate and facilitate MSE development across the regions
2. Identify the best insertion points to incorporate climate information into the science-to-management process
3. Better communication between scientists, managers, and stakeholders to understand needs and share information and resources

Activities – highlights

- An MSE Working Group was formed in 2016. The group comprises one individual from each Science Center who serves as the point of contact and lead for the Center's MSE activities. Additional participants in the Working Group come from HQ and Regional Offices. The primary objective of the working group is to encourage and guide the development and use of MSEs throughout NOAA Fisheries Science Centers, Regional Offices, and Fisheries Management Councils.
- ICE-FM - A team of 26 scientists from across the Science Centers, regional offices, and headquarters formed the Incorporating Climate and Environmental Information into Fisheries Management (ICE-FM) Working Group. The group identified six key steps in the science-to-management process needed to better account for and respond to climate impacts on fisheries, associated challenges and limitations for each step, and recommended actions to overcome them. The findings were published as a NOAA Technical Memo and journal article (Karp et al., 2018, Karp et al., 2019).
- Support for scenario planning on multiple fronts. Scenario planning is a tool to help fisheries managers better understand where flexibility and adaptability will be needed in the management process. The Office of Protected Resources supported the NE Region's pilot tests of the tool and helped develop a training course that has been offered at the U.S. Fish and Wildlife Service's National Conservation Training Center (NCTC). The Office of Sustainable Fisheries published a Technical Memorandum of case studies to help introduce the idea to fisheries managers (Frens and Morrison, 2020).
- Conceptual models - The Office of Protected Resources developed conceptual models to better understand climate impacts on protected species.
- Climate resource survey[8] - NOAA Fisheries worked with the Marine Fisheries Advisory Committee to identify the types of climate information needed by managers and stakeholders and how best to provide that information.

[8] NOAA website describing the climate resource survey results - https://www.fisheries.noaa.gov/resource/document/mafac-report-best-approaches-and-future-needs-prepare-fishing-communities-and

Progress summary
There are a variety of opportunities for NOAA Fisheries to better address changing ocean conditions in the science-to-fisheries management process, as identified by the ICE-FM effort. Implementing the recommended actions will better equip NOAA Fisheries to provide proper stewardship of living marine resources. Through increased efforts to develop and utilize MSEs, NOAA Fisheries will be better able to provide managers with the information they need to make climate-smart decisions.

Other Activities

In concert with the goals and activities under each of the NCSS objectives, the national activities also include efforts to promote cross-regional and international collaboration and exchange of information to help increase the delivery and use of climate information in resource management and adaptation actions.

Goal(s)

1. Promote the exchange of climate-related activities and information across the regions and with national and international partners

Activities – highlights

- Climate Adaptation Leadership Awards - Established in 2016 through a partnership with the Association of Fish and Wildlife Agencies, these awards "recognize exemplary leadership by individuals, agencies, businesses, and other organizations to reduce impacts and advance adaptation of the nation's vital natural resources in a changing world".
- Climate Quarterly - Organize a regular teleconference (every three months) to allow NOAA Fisheries personnel working on climate-fisheries issues to exchange information on accomplishments and activities in their region.
- Effects of Climate Change on the World's Oceans (ECCWO) 2018 - This international symposium is held every 4-5 years. In 2018, the 4th International Symposium was held in Washington, D.C. and was coordinated by a multi-organizational team consisting of NOAA Fisheries, PICES, ICES, IOC, and IMBeR and sponsored by over a dozen additional national and international organizations.
- National Climate Assessment - The 4th Assessment was released in 2018. NOAA Fisheries personnel helped coordinate the development of chapters on "Oceans and Marine Resources" and "Ecosystems, Ecosystem Services and Biodiversity".
- Integration of climate change considerations into Essential Fish Habitat (EFH) conservation activities, including development of the national "EFH Climate Guide," an internal white paper for resource managers; publication of regionally-specific climate change guidance for the EFH consultation process in the Greater Atlantic Region that has been socialized nationally and serves as a model document for other regional offices; and ongoing development of updated EFH climate change conservation recommendations for the Alaska region.

Progress summary
Over the last five years, the numerous national-level activities focused on raising awareness, exchanging ideas, and sharing information has facilitated national and international

collaborations and partnerships. These efforts have served to maintain and grow a community of practice of people working on climate and fisheries issues and has improved the capacity of NOAA Fisheries to address climate impacts on fish, protected species, fisheries, and fishery-dependent communities.

2.3 Conclusions

The progress made within each of the seven NCSS objectives has helped NOAA Fisheries be better prepared to respond to climate-related impacts on the Nation's living marine resources. The design of the NCSS put much of the focus on implementation through customized RAPs that account for regional needs and capacities. The National-level activities, highlighted above and in Table 2.1 below, helped to support the implementation through facilitation, coordination, communication, funding, and the leveraging of resources through partnerships. As funding has been a limiting factor in fully implementing the NCSS, many valuable partnerships with other NOAA Line Offices (i.e., NOAA Research), academia, non-governmental organizations (NGOs), and State and local agencies have provided needed funding and other resources dedicated to reaching shared goals as efficiently as possible.

Activities over the next 3-5 years will continue to focus on maintaining and developing partnerships and resources to increase the production, delivery, and use of climate-related information in fisheries management. One of the challenges has been identifying how best to measure progress toward achieving each of the NCSS objectives. In coordination with the regional teams, effort will be made to develop performance measures (metrics and milestones) that incorporate key attributes (i.e. specific, measurable, achievable, relevant, time-bound) designed to better assess progress toward NCSS goals.

2.4 Acknowledgements

Contributors to this section include: Roger B. Griffis, Jay Peterson, and Wendy Morrison. Special thanks to the editors and authors of the NOAA Fisheries Climate Science Strategy as well as the numerous individuals within NOAA Fisheries who contributed to the many achievements highlighted in this report.

Table 2.1. Highlights of activities addressing National goals under the seven NCSS objectives.

Informing Management (NCSS Obj. 1 – 3) • Establishment of an MSE Working Group to guide and encourage development and use of MSEs in each region • Identified on-ramps for climate information in the science-to-management process (ICE-FM) • Support for scenario planning in partnership with OPR and OSF
Understanding Mechanisms and Projecting Future Conditions (NCSS Obj. 4 & 5) • Fund research through the COCA-NMFS Climate and Fisheries program • Vulnerability Assessments for fishery species, protected species, and communities • Model development funded through the MAPP-NMFS partnership • OAR-NMFS Climate and Fisheries Initiative to improve forecasting capability
Infrastructure and Tracking Change (NCSS Obj. 6 & 7) • Establish and maintain capacity through coordination of RAP teams • Coordinate cross-regional communications – Climate Quarterly calls • Establish and promote international partnerships – DFO, ECCWO • Support Ecosystem Status Report development – IEA program • Species distribution tracking – Ocean Adapt

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3. Pacific Islands Regional Action Plan

3.1 Introduction

The Pacific Islands Regional Action Plan for climate science (PIRAP; Polovina et al., 2016) is a joint action plan between the Pacific Islands Fisheries Science Center (PIFSC), the Pacific Islands Regional Office (PIRO), and the Western Pacific Regional Fisheries Management Council (Council). Staff from all three entities worked together to assess the state of the region's climate science when the NOAA Fisheries Climate Science Strategy[9] (NCSS; Link et al., 2015) was released and then crafted a five-year plan to expand climate science and its role in regional living marine resource management and conservation. The PIRAP authors noted several strengths, particularly the high number of long-term time series in the region which allow for the detection of climate-related impacts on the ocean and ecosystems. Regional challenges were also assessed and were found to be related primarily to implementing climate-informed management strategies and projecting the effects of climate change on human communities. Building from the region's strengths, the PIRAP identified five priorities upon which to focus during the subsequent five years. These included incorporating climate into various aspects of living marine resource and habitat management, conducting vulnerability assessments, and continuing to advance the region's climate science. These priorities were supported by identifying specific actions that could be implemented, and which were aligned with the NCSS's seven objectives at both current and increased funding levels.

This chapter synthesizes PIRAP progress by NCSS objective, with the climate science objectives (7 - 4) discussed individually and the climate-informed management objectives (3 - 1) addressed collectively.

3.2 Activities, Progress, and Plans

Build and Maintain Adequate Science Infrastructure (Objective 7)

Goals

The PIRAP action items under this objective were centered on developing staff capacity through increased communication among regional staff, continued participation with the broader scientific community, and engagement with local communities. Additionally, three of the nine metrics laid out in the PIRAP were focused on building and maintaining science infrastructure. They are: 1) number of peer-reviewed publications produced that address climate change and climate impacts, 2) full-time equivalent (FTE) time (part time plus full time) devoted to climate science, and 3) number of climate workshops or conferences attended or convened.

[9] https://www.fisheries.noaa.gov/national/climate/noaa-fisheries-climate-science-strategy

Highlights
Of particular note is the region's Annual Collaborative Climate Science Workshop. This workshop brings together PIFSC, PIRO, and Council staff to discuss climate-related information needs and science that can help address those needs by improving communication between science providers and managers to enable climate-informed living marine resource management and conservation. Since its inception in 2017, this workshop has served as a model for other regions.

Progress summary
The Pacific Islands region has built its climate-science infrastructure through actions such as attending conferences and workshops, publishing peer-reviewed research that addresses climate change and climate impacts, and devoting staff time to climate science (Figure 3.1). Over the first five years of the NCSS, regional staff have published 50 peer-reviewed papers and reports (Appendix A) and attended or convened 19 workshops and conferences (Appendix B). PIFSC has increased FTE time by over 60% (from 240% to 390%) and increased the number of FTEs doing climate-related work by 46% (from 13 to 19 individuals). PIRO staff include climate information in NEPA, ESA, and other analyses.

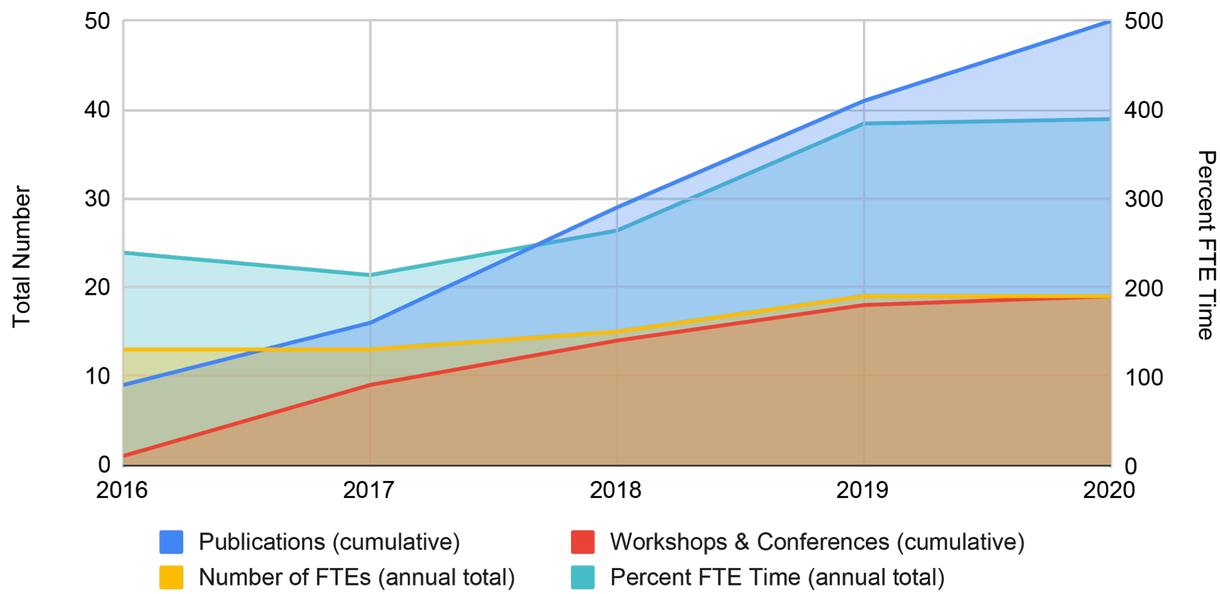

Figure 3.1. Timeline of growth in regional climate science capacity. Percent FTE time was determined by aggregating across all staff the proportion of time spent on climate-related work.

Looking ahead
The PIRAP noted the need for improved computer infrastructure, as well as staff capacity for activities such as downscaling climate model output to represent the region's coastal and coral reef ecosystems. These needs persist. For example, data available through the latest generation of earth system models (CMIP6[10]; Eyring et al., 2016) are even larger than data

[10] CMIP6 web page - https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6

available at the time the PIRAP was written. Housing relevant CMIP6 data for analysis and inclusion in ecosystem modeling efforts is challenging due to lack of easily accessible server space. Other climate-related data streams (e.g., autonomous vehicles, moorings, sensors, video cameras, still cameras, Structure from Motion) will also require significantly expanded computer infrastructure.

Track Change and Provide Early Warnings (Objective 6)

Goals
The ability to track change and provide early warnings requires robust long-term monitoring. Continued maintenance of the region's time series is essential for realizing many of the PIRAP's priorities, such as generating climate-informed habitat and species assessments and evaluating the food web effects of climate change. Therefore, one of the key actions identified in the PIRAP was to "maintain and enhance ongoing monitoring programs for insular and pelagic ecosystems, sea turtles, cetaceans, and monk seals and analyze these data to detect climate impacts" (Polovina et al., 2016). Two of the nine PIRAP metrics focused on the ability to track change: 1) number of long-term monitoring time series or assessments maintained and distributed, and 2) number of Ecosystem Status Reports that incorporate climate information and/or indices.

Highlights
The region's long-term assessments have enabled researchers to raise several early warnings for protected species in the Northwestern Hawaiian Islands. Long-term monitoring of Hawaiian monk seal habitat and demographics has revealed that sea level rise paired with recent severe weather as well as ongoing deterioration of abandoned infrastructure on Tern Island is posing a critical threat to the species. Likewise, monitoring of sea turtle nest temperatures has shown that as air temperatures continue to rise, so too do nest temperatures. Rising nest temperatures lead to feminization of sea turtle populations, and eventually embryonic death, both of which compromise species' long-term viability.

Progress summary
The Pacific Islands region maintains numerous time series that aid in the monitoring and tracking of climate change as it continues to unfold (Figure 3.2). These time series range from diver surveys and long-term instrument deployments in coral reefs and benthic environments to annual counts of sea turtles and endangered monk seals to autonomous passive acoustic monitoring for cetaceans. Through the use of these monitoring series, it has been possible to identify climate-related trends and impacts. These include the effects of extreme bleaching events as well as rising sea turtle nest temperatures. Time series of ocean and climate indicators are now a standard component of the Council's annual Stock Assessment and Fishery Evaluation (SAFE) reports. The West Hawai'i Integrated Ecosystem Assessment has produced two Ecosystem Status Reports that include indicators for the climate and ocean, commercial and non-commercial pelagic fisheries, and human dimensions. Additionally, National Coral Reef Monitoring Program status reports[11] have been produced for all of the

[11] National Coral Reef Monitoring Progam website - https://www.coris.noaa.gov/monitoring/status_report/

region's coral reefs. Within the past five years, additional funding has enabled the expansion of fishery-independent bottomfish monitoring to include temperature monitoring.

<table>
<tr><th>2016</th><th>2017</th><th>2018</th><th>2019</th><th>2020</th></tr>
<tr><td colspan="4">SAFE report ocean and climate indicators: North Pacific pelagic and archipelagic areas</td><td></td></tr>
<tr><td colspan="4">Green sea turtle nest temperature logging: NWHI</td><td></td></tr>
<tr><td></td><td></td><td>Hawksbill nest temperature logging: MHI</td><td></td><td></td></tr>
<tr><td></td><td colspan="4">Sea turtle monitoring: PRIA</td></tr>
<tr><td colspan="4">Sea turtle surveys: Guam & CNMI</td><td></td></tr>
<tr><td colspan="4">Green sea turtle nesting abundance: NWHI</td><td></td></tr>
<tr><td colspan="4">Green sea turtle demographic rates: NWHI</td><td></td></tr>
<tr><td colspan="4">Green sea turtle remigration monitoring: NWHI</td><td></td></tr>
<tr><td colspan="4">Monk seal surveys: NWHI & MHI</td><td></td></tr>
<tr><td colspan="5">Acoustic cetacean monitoring: MHI, NWHI, PRIA, & CNMI</td></tr>
<tr><td>Visual cetacean surveys: Guam & CNMI</td><td></td><td colspan="3">Visual cetacean surveys: Guam & CNMI</td></tr>
<tr><td colspan="2">Visual cetacean surveys: MHI</td><td></td><td></td><td>Visual cetacean surveys: MHI</td></tr>
<tr><td>Coral reef ecosystem monitoring: AS</td><td></td><td>Coral reef ecosystem monitoring: AS</td><td></td><td></td></tr>
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<tr><td></td><td></td><td></td><td></td><td>Coral reef bleaching surveys: MHI</td></tr>
<tr><td colspan="5">Longline logbook data: Hawaii, American Samoa</td></tr>
<tr><td colspan="5">Pacific Islands Region Observer Program data: Hawaii, American Samoa</td></tr>
<tr><td colspan="5">Lancetfish diet data: Hawaii</td></tr>
<tr><td></td><td></td><td>Fishing community vulnerability indicators: AS, CNMI, Guam, & MHI</td><td></td><td></td></tr>
<tr><td></td><td>Survey of fisher attitudes and perceptions of climate change: MHI</td><td></td><td></td><td></td></tr>
<tr><td colspan="5">American Community Survey-based indicators: MHI</td></tr>
<tr><td>West Hawaii Integrated Ecosystem Assessment</td><td></td><td></td><td>West Hawaii Integrated Ecosystem Assessment</td><td></td></tr>
<tr><td></td><td></td><td>Coral Reefs: American Samoa, Guam, CNMI, MHI, NWHI, & PRIA</td><td></td><td></td></tr>
</table>

Figure 3.2. Time series of persistent maintenance of regional monitoring series that span from the physical environment through marine ecosystems to fishing communities (light blue), along with Ecosystem Status Reports (dark blue). Note: this figure was prepared in September 2020 and thus may not fully capture 2020 activities.

Beyond simply monitoring conditions, regional staff are developing new analytical and modeling approaches to detect change and provide early warnings. PIFSC scientists are developing methods to better apply existing National Coral Reef Monitoring Program datasets to questions of resilience at small spatial scales. These methods have shown patterns of temporal ecological change previously masked by large spatial reporting sectors, and these patterns highlight areas of ecosystem resilience (Oliver et al., 2020a). PIRO staff have also performed studies at much finer spatial scales around Saipan, following six years of disturbance events, to capture demonstrated resilience with an emphasis on resilience following the major thermal stress event of 2017 (Maynard et al., 2019).

Regional staff have also worked to combine evidence of past change with future projections to provide early warnings of climate effects. These warnings include local-scale projections of when annual coral bleaching is anticipated across the globe. In the Pacific Islands region, annual bleaching is projected beginning in 2035 - 2045 (van Hooidonk et al., 2016). Work is currently underway to update these projections with the new CMIP6 Shared Socioeconomic Pathways.

In Hawai'i, a coalition of partners, including PIRO, PIFSC, Hawai'i's Department of Land and Natural Resources, and several universities, collaborated to track the recent 2019 major coral bleaching episode. Scientists used a network of small satellites to track the event in near-real-time, providing high resolution images of the corals before, during, and after the bleaching event. This information was provided to the public and helped to establish a database for coral bleaching impacts that can inform management.

Looking ahead

Autonomous monitoring and high-performance computing will be important for future progress. The ship time needed to maintain the many time series highlighted above is steadily declining. Autonomous platforms such as Saildrones and Seagliders, as well as moorings, could compensate somewhat for the loss of ship time available for high seas surveys. Fixed sensors, moorings, cameras, and expanded shore-based, small-boat efforts could potentially compensate for the loss of surveys in shallow waters (i.e., reefs and atolls). Similarly, remote camera or video monitoring and unmanned aerial systems could be further developed to augment sea turtle and monk seal monitoring. However, we note that these methods will likely never be able to fully substitute for ship-based field work.

High-performance computing will be particularly important for tracking change in coral reef communities, where new approaches like Structure from Motion are coming into practice. It will also be needed to assimilate the data gathered from model downscaling efforts.

In the Pacific, active coral reef restoration is relatively new. Managers recognize that while conventional management of local stressors (e.g., water quality, coastal development, fishing impacts) is necessary, it will not be sufficient to help reefs resist and recover from climate change. Restoration plans are needed to guide management, as is the development, implementation, and evaluation of science-based coral restoration projects. Through a cooperative agreement, NOAA and The Nature Conservancy have started restoration planning with the four Pacific island jurisdictions of Hawai'i, Guam, American Samoa, and the Commonwealth of the Northern Mariana Islands (CNMI). This project will build capacity by helping each jurisdiction develop coral restoration plans, providing training opportunities and technical assistance, and fostering learning exchanges. In Hawai'i, work will include scientific assessments to inform restoration and implement and evaluate in-water coral restoration projects at pilot sites in the main Hawaiian Islands. This project will serve as a catalyst for effective restoration throughout the Pacific.

Understand Mechanisms of Change (Objective 5)

Goals

At the time the NCSS was released, much of the region's work on understanding mechanisms of change was focused on single species. While this enabled the early warnings discussed above, it fails to fully capture the role of these species in their larger ecosystem. Therefore, the PIRAP highlighted the need to understand mechanisms of climate-driven change across the food web, particularly at mid-trophic levels. To realize this goal, the PIRAP includes a mix of model-based and empirical research-oriented action items.

Highlights

One project that is providing insight into mechanisms of change is an ecosystem-based approach to addressing protected species interactions with Hawai'i's longline fishery. While not focused specifically on climate change, the results can help inform climate projections for protected species. This project is exploring the relationship between oceanographic conditions and interaction rates. One of the main products is a map of interaction probabilities and a ranking of the relative importance of oceanographic features that appear to define the interactions. Early results highlight that there is a greater probability of leatherback sea turtle longline interactions northeast of Hawai'i and that mixed layer depth is among the better predictors of interactions. Both of these pieces of information can help inform climate projections for this species. Ocean warming is projected to increase stratification in the subtropical oceans, which will lead to changes in mixed layer depth. Furthermore, Hawai'i's longline fishery is expanding its effort in the region where interactions are greater (Woodworth-Jefcoats et al., 2018), and this expansion is projected to continue in tandem with climate change (Woodworth-Jefcoats et al., 2017). Additional work aimed at understanding drivers of interactions includes the Council's 2017 albatross workshop (Hyrenbach et al., 2021). Again, while not exclusively focused on climate change, understanding how environmental conditions affect interactions can enable climate change to be incorporated into broader management considerations.

Progress summary

The region has developed several climate-informed food web models to help gain understanding into the mechanisms of climate-induced change. These models include: 1) Ecopath with Ecosim models to assess the potential impacts of climate change on endangered monk seals in the Northwestern Hawaiian Islands (Weijerman et al., 2017), 2) the efficacy and tradeoffs of multiple management scenarios in West Hawai'i (Weijerman et al., 2018), 3) a multi-species size spectrum model of the pelagic central North Pacific (Woodworth-Jefcoats et al., 2019), and 4) an Atlantis model for both Guam (Weijerman et al., 2015) and the main Hawaiian Islands (currently under development). Economic models were developed to project future longline fishing trip costs as well as fishing location choice. In addition to this modeling work, additional funding has enabled work toward the construction of species distribution models from telemetry data. These distribution models will enable future work that will use climate model output to project species' spatial redistribution under climate change. In turn, the ecosystem and fishery effects of these redistributions can be incorporated into the economic models discussed above.

The region has also examined patterns of marine heat waves across the central Pacific. Combining both *in situ* and satellite data showed that "depth refugia", or areas where coral reefs are likely to experience relief from sea surface heat stress in deeper water, are rare across the central Pacific (Venegas et al., 2019).

Looking Ahead
Going forward, attention should be directed towards understanding the effects of ocean acidification on pelagic ecosystems, particularly on the plankton and micronekton communities, and on larval fish development. These areas of ocean acidification research are relatively unexplored, compared to coral reefs, and may potentially impact the region's most valuable commercial fishery - a pelagic longline fishery for bigeye tuna. Additionally, a better understanding of the physiological effects of climate change is needed. Climate-driven changes in life history traits, such as growth and fecundity, once understood, can then be incorporated into stock assessments and recovery plans.

Project Future Conditions (Objective 4)

Goals
In order to project future ecosystem and community conditions under climate change, the PIRAP includes several action items that make use of climate and earth system model output. Among these action items, and among the PIRAP's highest priorities, are climate vulnerability assessments.

Highlights
The Pacific Islands Vulnerability Assessment (PIVA) project assessed the susceptibility of 83 marine species across the Pacific Islands region to the impacts of climate change projected to 2055. The invertebrate group ranked as most vulnerable, and pelagic and coastal groups not associated with coral reefs ranked as least vulnerable. Sea surface temperature, ocean acidification, and oxygen concentration were the three main exposure drivers of vulnerability. Early life history and settlement requirements were the most data deficient of the sensitivity attributes considered in the assessment.

Progress summary
The above-mentioned modeling work is projecting future conditions in regional marine systems ranging from coral reefs to pelagic fishing grounds. In order to understand the fishery impacts of changing future conditions, work is underway to project future longline fishing trip costs for Hawai'i's commercial bigeye tuna and swordfish fisheries. Additional statistical downscaling work is projecting future ocean temperatures at coral reefs around the world. A wide range of vulnerability assessments have been conducted for species and systems in the Pacific Islands

region (Figure 3.3). In addition to the fish and invertebrate vulnerability analyses discussed above, vulnerability analyses have also been completed for coral reefs[12], anchialine pools[13], and coastal communities (Kleiber et al., 2018). Building on this social vulnerability work, PIFSC scientists released Coral Reef Resilience and Social Vulnerability reports for American Samoa, CNMI, Guam, and the Main Hawaiian Islands (Oliver et al., 2020c, 2020d, 2020e, 2020f). The completion of vulnerability assessments was one of the PIRAP's nine metrics.

Looking Ahead

Going forward, there are plans to extend species vulnerability assessments to fishing communities. For example, communities' potential vulnerability to climate-driven impacts on species of particular cultural or commercial value will be assessed. Expanding the capacity for spatially explicit food web models will also enhance the ability to project future conditions. This would allow for more nuanced projections of how species' vulnerability might vary across their full habitat. It could also provide insight into vulnerability across life stages, for example if spawning grounds are found to be more or less heavily impacted by climate change.

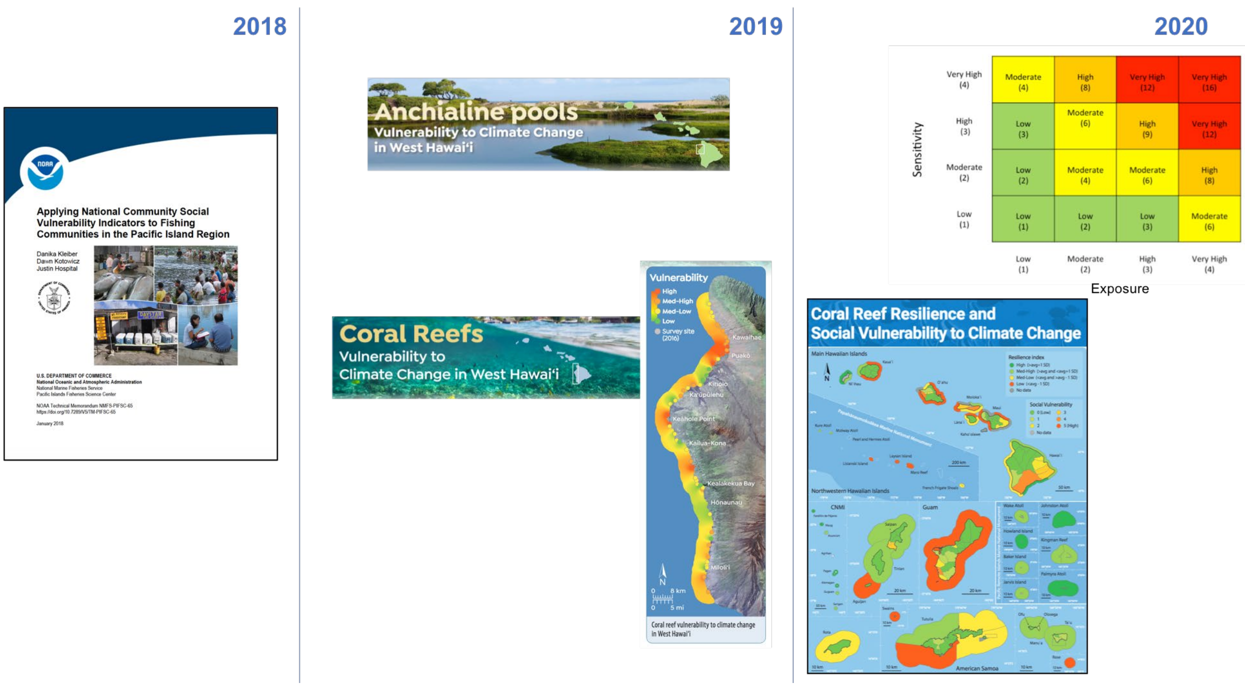

Figure 3.3. Vulnerability assessments completed in the Pacific Islands region to date.

[12] PDF of coral reef vulnerability assessment - https://www.integratedecosystemassessment.noaa.gov/sites/default/files/2019-04/2019_Vulnerability%20to%20Climate%20Change_Coral%20Reefs%20%281%29.pdf
[13] PDF of anchialine pools vulnerability assessment - https://www.integratedecosystemassessment.noaa.gov/sites/default/files/2019-04/2019_Vulnerability%20to%20Climate%20Change_Anchialine%20Pools.pdf

Informing management (Objectives 1-3)

Goals
PIRAP goals related to informing management include developing adaptive management processes, robust management strategies, and climate-informed reference points.

Highlights
Incorporating climate variables into regional stock assessments is a growing area of research and was one of the PIRAP's metrics. Currently, the bottomfish stock assessment (Langseth et al., 2018) includes a measure of winds that could potentially be expanded into a climate framework. Data being collected on research bottomfishing sets could also contribute to a climate-informed aspect of this assessment. Work is also underway to include a measure of phytoplankton size in the swordfish stock assessment (Sculley et al., 2018). This measure is derived from satellite ocean color and sea surface temperature, and is another avenue which could potentially be expanded in a climate framework.

Progress summary
Climate impacts are evaluated in all regional National Environmental Policy Act (NEPA) analyses, as well as in Endangered Species Act (ESA) Section 7 consultations, listing and status reviews, and recovery plans. Climate indices have also regularly been included in the Council's SAFE Reports since 2015. A Marianas Trench Marine National Monument plan was developed in coordination with USFWS and with input from PIFSC. The draft includes a Climate Change Action Plan with relevant background and targeted climate-smart activities; publication is anticipated in 2020.

The Council held community-based workshops to facilitate information exchange and assemble information on traditional knowledge as it pertains to climate change. Train-the-trainer workshops with the Council's various advisory bodies were conducted in partnership with NOAA in 2017 throughout the region. Work is ongoing to partner with members of the advisory bodies to conduct climate and fisheries workshops with fishing communities in the region. Traditional knowledge pertaining to climate change was assembled and provided to the NOAA Scientific Advisory Board in 2016 and to the Kahana community in 2017. Traditional knowledge was also discussed at the Council's April 2018 Marine Planning & Climate Change Committee meeting, and information may inform future climate monitoring/research.

Several of the ecosystem indicators and modeling efforts described earlier in this report are already being used to inform regional management. For example, the Ecopath with Ecosim model for West Hawai'i (Weijerman et al., 2018) is being used by State of Hawaiʻi managers as they seek to balance ecological resilience with the provisioning of ecosystem services. Projections of future coral reef bleaching (van Hooidonk et al., 2016), as well as several indicators from the West Hawai'i Ecosystem Status Reports (PIFSC, 2016, Gove et al., 2019), are being used to inform the State's Marine 30x30 initiative. PIFSC scientists have also applied the Coral Reef Resilience and Social Vulnerability analysis to provide perspectives on how to prioritize management action under Resilience Based Management (Oliver et al., 2020b). Their work suggests that strategies that prioritize management action according to rankings by an aggregate resilience metric perform well under a diverse set of other prioritization metrics, including diversity, exposure, and social vulnerability.

PIRO staff are leading a pilot nursery effort in the CNMI that is tracking environmental conditions and growth performance across a range of corals, including the ESA-listed coral *Acropora globiceps*, to better understand and inform future upscaling and outplanting efforts. The pilot coral nursery effort in the CNMI continues to expand as more structures are added, a greater diversity of corals are integrated, outplanting begins, and extreme environmental conditions create new opportunities to document performance. The pilot nursery has demonstrated 99% survivorship for coral fragments thus far and the current structure designs were able to stand up to ocean conditions generated by typhoon Hagibis in October 2019 that destroyed several shallow-water instruments.

Looking Ahead

It will be important to establish and sustain relationships among scientists, managers, fishing communities, industry, and other stakeholders in order to expand the implementation of adaptive management processes. One issue that warrants attention going forward is emerging and disappearing fisheries in this region. Fisheries will be affected by numerous factors including changing environmental conditions, shifting species distributions and community interactions, and fishing behavior responses to regulatory, environmental, and economic drivers. Future monitoring efforts should include all of these influences in order to best inform adaptive management approaches.

With regard to producing climate-informed stock assessments, a current hurdle is the availability of skillful seasonal- to decadal-scale forecasts of oceanographic and biogeochemical variables. These are needed in order to extend stock assessments into the near future. Once that gap is bridged, it may be possible to incorporate climate-scale projections into stock assessments conducted by PIFSC staff and others.

PIRO and PIFSC are building a partnership to expand the data management and analysis efforts associated with the coral nursery effort in the CNMI. Another important resilience-based management option for possible future implementation is expanding the science on the importance of herbivory in coral reef ecosystems and related management approaches (i.e., herbivore protected areas) to mitigate impacts of coral bleaching and improve reef fisheries. Herbivory is an important ecological process that aids in preventing phase shifts from coral dominance to algae overgrowth. Herbivorous species of fish and invertebrates, such as urchins, help keep algae populations in check, allowing corals to grow and reproduce, and also creating healthy substrate conditions for new coral larvae to settle. Herbivore management areas, such as the Kahekili Herbivore Fisheries Management Area on Maui, have been successful in increasing biomass of both herbivores and crustose coralline algae (Chung et al., 2019).

3.3 Conclusions

Successes and Lessons Learned

Over the first five years of implementing the NCSS in the Pacific Islands region there have been a number of successes (described above and highlighted in Table 3.1) and lessons learned. There has been a robust appetite for scientist-manager collaboration. Work undertaken in recent years has built strong foundations from which to build. Regional collaboration to address critical threats at Tern Island is a prime example. Even for more routine research and management issues, there is an increased interest in early collaboration in order to understand management needs and shape research as it progresses.

Another highlight from the early implementation of the NCSS is the expansion of climate science capacity. This expansion includes not only staff time and research output, but also engagement with stakeholders through activities such as the "Train-the-trainer" workshops and incorporation of climate indicators into annual SAFE reports. These efforts are critical to expanding awareness of the threats posed by climate change. They also help create a better link between climate science and management needs.

Focusing on the effects of climate change in the Pacific Islands region has highlighted the fact that, for many species and habitats, baseline information to which climate impacts can be compared is still lacking. Identifying these gaps, such as better understanding species distributions and interactions, will help focus research going forward. The PIRAP activities and collaborations also helped to highlight the considerable scope for overlap between programs and projects. For example, data gathered for a specific monitoring project can inform broader climate projections, and sensors could be added to existing instrumentation to gather data needed by other programs.

Potential Focal Areas for a RAP 2.0

In the next phase of NCSS implementation, it will be important to maintain focus on communication and collaboration between scientists and managers, as well as with fishing communities and industry. Such collaborations can provide a conduit for sharing observations and concerns, understanding behavioral responses, ground-truthing model assumptions and output, expanding cooperative research opportunities, and much more. Continued support for long-term monitoring will also be essential. As ship time declines and fewer resources are allocated to time series maintenance, our ability to detect change will deteriorate. Likewise, our ability to establish needed baseline information on species' distributions and life history parameters will be hampered.

Another potential focal area for the next phase of NCSS implementation is collaboration with academia and others to address basic science gaps that fall outside the scope of NMFS's work. For example, the research needed to better understand physiological effects of environmental change is typically conducted by academia. This includes work on the effects of ocean warming and acidification, stressors that are already impacting ecosystems across the Pacific Islands region. A national-level competition could encourage such collaboration. Within NOAA, continued cross-line-office collaboration will be needed to ensure climate and earth system modeling efforts adequately address future needs. The joint NMFS-OAR Climate and Fisheries Initiative includes work that would help address this need.

Potential Metrics and Milestones for a RAP 2.0

The PIRAP's science-oriented metrics were clearly quantifiable, while the management-oriented metrics proved too broad to quantitatively measure progress toward. In a subsequent PIRAP, it would be ideal to provide more realistic metrics for measuring progress toward implementing management that takes into account climate impacts. Future metrics, both of science and management focus, should include targets or deliverables. Such targets would place progress in the context of larger regional and NCSS goals. Finally, with the release of CMIP6 data and the Intergovernmental Panel on Climate Change (IPCC's) AR6 (Sixth Assessment Report), there will be new information and data that can be incorporated into regional analyses and management. These climate products should be used in place of earlier information to ensure that the region can appropriately meet the threats posed to living marine resources by climate change.

Table 3.1. A selection of PIRAP activities grouped by NCSS objective.

Informing Management (NCSS Obj. 1 – 3) • Inclusion of climate indicators in SAFE reports • Evaluation of climate impacts in NEPA analyses and ESA consultations • Climate Action Plan for Marianas Trench Marine National Monument • Community-based workshops focused on connecting the Council to LK/TK
Understanding Mechanisms and Projecting Future Conditions (NCSS Obj. 4 & 5) • Development of climate-informed food web models, such as Ecopath with Ecosim for monk seals, West Hawai'i management scenario analyses, size spectrum model of the pelagic central North Pacific, and an Atlantis model for Guam and Hawai'i • Economic model development • Species distribution models • Marine heat-wave impacts • Pacific Islands Vulnerability Assessment
Infrastructure and Tracking Change (NCSS Obj. 6 & 7) • Annual Collaborative Climate Science Workshop • Maintain monitoring programs, including coral reef diver surveys, benthic environments and long-term monk seal habitat and demographics • West Hawai'i Ecosystem Status Report • Multi-agency coral bleaching tracking effort

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3.4 Appendix A - Climate-Related Publications

Publications are listed by the year in which they were first published online, which in some cases precedes the eventual publication year.

2016

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3.5 Appendix B - Climate-related Workshops & Conferences

2016

North Pacific Marine Science Organization (PICES) Annual Meeting included several climate-theme sessions and workshops
https://meetings.pices.int/meetings/annual/2016/pices/scope

2017

1st Annual Collaborative Climate Science Workshop
https://www.fisheries.noaa.gov/event/annual-collaborative-climate-science-workshop-pacific-islands-2017

National Protected Species Assessment Workshop
https://spo.nmfs.noaa.gov/sites/default/files/TMSPO172.pdf

Hawai'i Conservation Conference
https://www.hawaiiconservation.org/conference/2017-hawaii-conservation-conference/

Train-the-trainer workshops

Albatross workshop
Hyrenbach, K.D., A. Ishizaki, J.J. Polovina, and S. Ellgen (eds). In Review. The Factors Influencing Albatross Interactions in the Hawai'i Longline Fishery: Towards Identifying Drivers and Quantifying Impacts. 7-9 November 2017. NOAA Tech Memo.

2018

2nd Annual Collaborative Climate Science Workshop
https://www.fisheries.noaa.gov/event/annual-collaborative-climate-science-workshop-pacific-islands-2018

4th Symposium on the Effects of Climate Change on the World's Oceans
https://meetings.pices.int/meetings/international/2018/climate-change/scope

Hawai’i Conservation Conference
https://www.hawaiiconservation.org/conference/2018-hawaii-conservation-conference/

PIVA workshop

Fourth WESTPAC Workshop on Research and Monitoring of the Ecological Impacts of Ocean Acidification on Cora Reef Ecosystems
http://iocwestpac.org/news/854.html

2019
3rd Annual Collaborative Climate Science Workshop
https://www.fisheries.noaa.gov/event/annual-collaborative-climate-science-workshop-pacific-islands-2019

Sea turtle climate vulnerability assessment workshop

Hawai’i Conservation Conference
https://www.hawaiiconservation.org/conference/2019-hawai%ca%bbi-conservation-conference/

OceanObs
http://www.oceanobs19.net/

2020
NOAA OA Community Meeting and Mini-Symposium
https://cpaess.ucar.edu/meetings/2020/ocean-acidification-program

4. Bering Sea Regional Action Plan

4.1 Introduction

The Bering Sea Regional Action Plan (RAP) was published in 2016 (Sigler et al., 2016) and was developed to increase the production, delivery, and use of climate-related information required to fulfill the NOAA Fisheries mission in the regions. The Bering Sea RAP identifies priority needs and specific actions to implement the NOAA Fisheries Climate Science Strategy[14] in the respective regions over a three to five year time period. The Bering Sea RAP focuses on the southeastern Bering Sea, a region that supports large marine mammal and bird populations and some of the most profitable and sustainable commercial fisheries in the United States.

The eastern Bering Sea (EBS) supports some of the most valuable commercial fisheries in the world. Large numbers of seabirds and marine mammals also are found here and subsistence harvests are a critical resource for coastal communities. Evidence reveals that climate-related changes in ocean and coastal ecosystems are already impacting the fish, seabirds, and marine mammals in the region as well as the people, businesses, and communities that depend on these living marine resources. Demand for actionable information on how, why, and when climate change will impact this region is growing.

The Bering Sea Regional Action Plan highlighted more than 30 projects focused on climate science that were active in the region at the time (Figure 4.1, Table 4.1).

[14] https://www.fisheries.noaa.gov/national/climate/noaa-fisheries-climate-science-strategy

Figure 4.1. Summary of 2017 climate linked research from the Bering Sea RAP. Asterisks indicate projects that would be supported if additional funding was available as of 2017. The remaining projects were expected to be supported if funding remained at the 2017 level.

Table 4.1. List of projects and web-links for key climate related research programs noted in the 2017 Bering Sea Regional Action Plan. Note: weblink URLs are listed in footnotes on subsequent pages of the chapter.

Project	Web-Link	NCSS Objective
NPFMC Bering Sea Ecosystem Plan	FEP	Objective 2
Alaska Climate Integrated Modeling Project (ACLIM)	ACLIM	Objectives 1-4
Climate vulnerability assessment for the SE Bering Sea	EBS VA	Objective 4
Belmont Forum Project	RAC Arctic	Objective 2
Recruitment Processes Alliance (RPA)	EcoFOCI	Objectives 5-7
Loss of Sea Ice Research	LOSI	Objective 6
Ocean acidification research	OA AFSC	Objective 5

Project	Web-Link	NCSS Objective
Lenfest research on Northern fur seals	Lenfest Fur Seals	Objective 5
Assessments of economic and human community impacts	Community Profiles	Objectives 4-6
Alaska Integrated Ecosystem Assessments and Alaska Ecosystem Status Reports	Alaska IEA and ESR	Objective 6
Standard Ecosystem Monitoring		Objective 7

This document provides a five year synthesis of the progress that has occurred since the publication of the Bering Sea Regional Action Plan. The document is structured to inform the reader of NOAA's progress towards the goals and objectives of the NCSS. It is structured around each of the NCSS objectives (1-7 in reverse order).

4.2 Activities and Progress

Build and Maintain Infrastructure (Objective 7)

Goals
Build and maintain the science infrastructure needed to fulfill NOAA Fisheries mandates under changing climate conditions.

- Maintain existing surveys and stock assessment infrastructure
- Maintain process oriented surveys
- Maintain existing laboratory infrastructure
- Maintain predator prey research infrastructure
- Maintain existing ecosystem modeling capability
- Maintain existing assessments of economic impacts (e.g., economic SAFE)
- Maintain existing community profiles[15]
- Maintain international research partnerships
- Build and maintain critical research partnerships
- Communicate climate risks
- Training, education, and outreach
- Invest in modeling

Activities
During the period 2015 to present, the AFSC has continued to support the fishery dependent and fishery independent field operations necessary to fulfill its mandates under changing climate conditions in the Bering Sea.

[15] Alaska fishing community profiles website - https://archive.fisheries.noaa.gov/afsc/REFM/Socioeconomics/Projects/communities/profiles.php

NMFS's commitment to the collection, and use, of in-season fishery dependent data to manage catch is a central pillar of the region's sustainable fisheries approach. In the last five years the fishery observer program implemented a fully randomized sampling program (Cahalan and Faunce, 2020) and electronic monitoring. These improvements to data collection continue to provide the infrastructure needed to detect and understand the climate impacts on fish, shellfish and fisheries.

Fishery independent monitoring also provides critical on-going observations. Standard long-line, acoustic-trawl (e.g., Honkalehto et al., 2018) and bottom trawl surveys (e.g., Lauth et al., 2019) were conducted to assess the distribution, condition, age or size composition, and abundance of EBS groundfish, crab, and euphausiids. Ecosystem surveys were conducted to assess and monitor the condition, distribution, and density (as measured by catch per unit effort [CPUE]) of larval and juvenile groundfish and salmon and the species composition, distribution, and density of phytoplankton and zooplankton. In 2014 and 2018, the eastern Bering Sea slope survey was not conducted (Figure 4.2). In 2017, the AFSC initiated bottom trawl surveys of the Northern Bering Sea (NBS) shelf region as part of the Loss of Sea Ice (LOSI[16]) funded research plan. Sampling in the NBS covered 198,858 km^2 of the Bering Sea shelf area in addition to the standard sampling of the EBS area of 492,897 km^2. The timing of this addition was fortuitous because the region had experienced a marine heatwave in 2015/16 and an unprecedented low sea ice year in the winter of 2017/18 (Walsh et al., 2017; Stabeno and Bell, 2019). Results of this survey revealed a spatial shift in the distribution of Pacific cod. This spatial shift persisted in 2018 and 2019 (Stevenson and Lauth, 2019). The bottom trawl survey sampling included substantial analysis of groundfish food habits (stomach collections) and fish condition data, and ecosystem-level impacts of the distributional shift on productivity and food web structure are being quantified.

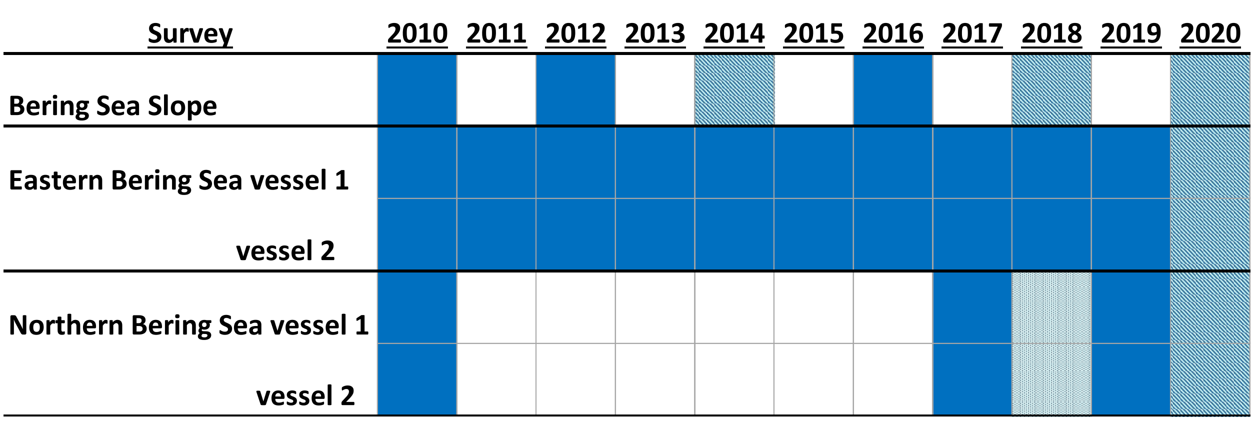

Figure 4.2. Summary of completed (solid), partial (dotted) and cancelled (diagonal lines) Alaska Fishery Science Center bottom trawl surveys 2010-2020. All 2020 cruises canceled due to COVID-19 restrictions.

[16] Loss of Sea Ice Research website - https://www.fisheries.noaa.gov/alaska/ecosystems/habitat-and-ecological-processes-research-regarding-loss-sea-ice

Through the long standing research partnership between AFSC and the Pacific Marine Environmental Laboratory (PMEL, EcoFOCI[17]), seasonal fisheries oceanographic surveys were conducted over the eastern Bering Sea shelf. These surveys collect physical oceanographic measurements as well as data on phytoplankton, zooplankton, and larval fish. Time series data indicate changes in timing of the spring phytoplankton bloom, increases in abundances of warm-affinity larval fish species, and declines in abundances of cold-affinity copepod species. In addition, the Bering Arctic Subarctic Integrative Survey (BASIS[18]) has been conducted annually in the NBS and biennially (even years) in the southeastern Bering Sea shelf. This survey deploys a surface trawl and mid-water acoustics targeting juvenile salmon and pollock. They also provide indices for phytoplankton and zooplankton biomass and species assemblages. Time trends in the total stations sampled during BASIS surveys show a decline in recent years (Figure 4.3).

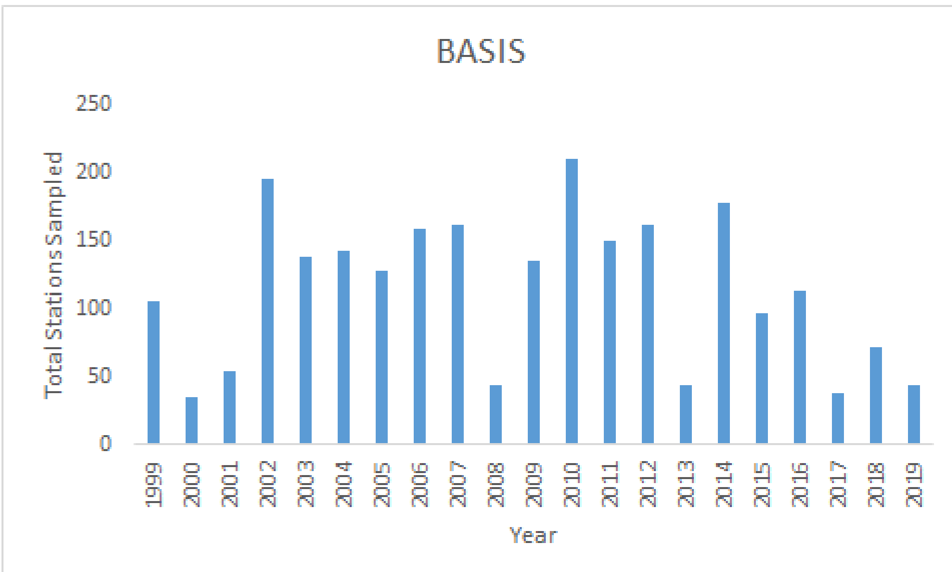

Figure 4.3. Total stations sampled by year during the BASIS (southern and northern Bering Sea combined) surveys. Sampling occurs annually in the NBS and biennially (even years) in the SBS. In 2015, external funds were provided to sample some stations in the SBS during 2015.

Laboratory capabilities including food habits, genetics, assessments of thermal tolerance and vulnerability to changes in pH, aging, and behavioral ecology were maintained, however some were reliant on unpredictable funding.

Progress summary

Advanced technologies were used to collect information from remote locations. For example, deep-sea circulation in the Bering Sea was evaluated using Argo Data (Johnson and Stabeno, 2017). Ice dependent seals were monitored using unmanned aerial surveys (Angliss et al., 2018). An exciting new development was the advancement of uncrewed surface vehicles

[17] EcoFOCI program website - https://www.ecofoci.noaa.gov/
[18] Website for the BASIS survey - https://www.fisheries.noaa.gov/alaska/population-assessments/bering-arctic-and-subarctic-integrated-survey

(USVs, developed by Saildrone™) for use in collecting oceanographic (Mordy et al., 2017) and fish backscatter (De Robertis et al., 2019) data. Transformative aging methods have been introduced that hold the potential for rapidly aging groundfish (Helser et al., 2018). Data from these platforms enhance and improve the Alaska Fisheries Science Center's (AFSC) ability to monitor changes in ocean conditions and the responses of fish and shellfish to these changes.

With the exception of the slope regions of the eastern Bering Sea, NOAA has met its goal of maintaining and expanding its climate science infrastructure through the use of base funding and external grants. In recent years, the Bering Sea RAP had to supplement funding for moorings in the Bering Sea. Likewise, advancements in new technologies were heavily leveraged by external grants. The critical need for ecosystem moorings in the Bering Sea has been demonstrated by the high number of citations that utilize information from these moorings. Finding a mechanism to ensure funding for PMEL moorings is a high priority in the future. Evidence of the rapid transition from research to operations for USVs is underscored by the deployment of three Saildrones™ in 2020 as a partial replacement for the NMFS standard acoustic-trawl surveys for pollock; an action necessitated by the inability of NOAA to deploy NOAA research vessels during a global pandemic.

Performance relative to reaching these objectives are measured as described below.

- The successful deployment of fishery independent surveys including: post-juvenile fish and shellfish surveys, juvenile fish surveys, and ichthyoplankton/zooplankton surveys with underway oceanographic sampling to provide synoptic understanding of marine mammal, fish, and shellfish responses to environmental change. 100% of existing Bering Sea Shelf surveys were maintained. Coverage of the eastern Bering Sea slope region was missed in 2014 and 2018. Additional surveys were added in the northern Bering Sea in 2017, 2018, and 2019. While the inclusion of surveys of the NBS increased the survey footprint by approximately 40%, coverage of the Bering Sea slope was diminished.
- Deployment of three upward looking moorings with advanced sensors to increase coverage of pollock movement across the US - Russian border.
- The successful deployment of fishery dependent data collections.

Tracking Change (Objective 6)

Goals

Track trends in ecosystems, LMRs, and LMR-dependent human communities and provide early warning of change.

- Produce Alaska Integrated Ecosystem Assessment and Ecosystem Considerations Chapter (Renamed to Ecosystem Status Report)
- Maintain Standard ecosystem monitoring
- Loss of Sea Ice research
- Coastal assessments
- NOAA Moorings

Activities

In partnership with PMEL, oceanographic monitoring surveys were conducted along the 70 m isobath line and moorings were deployed and maintained (Tabisola et al., 2017; Lomas et al., 2020). These surveys and moorings provided important ecosystem indicators that were reported to the NPFMC as contributions to the Bering Sea Ecosystem Status Report[19] (ESR).

As noted earlier, NOAA has invested in diverse fishery dependent and fishery independent ecosystem monitoring. The AFSC and Alaska Department of Fish and Game) (ADF&G) use this information in population dynamics models in stock assessments to track time trends in recruitment, growth, age composition, reproductive potential, and total biomass. Most of these assessments are age- or size-based and some include ecosystem linkages (Lynch et al., 2018). Ecosystem linkages include temperature effects on catchability, and bottom temperature effects on survey availability (Thorson, 2019; Thorson et al., 2020), temperature effects on growth and consumption (Holsman et al., 2016), and predation impacts on CPUE (Hanselman et al., 2018) or juvenile survival (Spencer et al., 2016). Collectively, these assessments provide the best available scientific information on recent changes in stock status in response to climate variations.

A framework for qualitatively evaluating relationships between time trends in ocean variables and key vital rates used in assessments has been improved through the adoption of Ecosystem and Socio-economic Profiles (ESPs) (Shotwell et al., in prep.). The ESP process was initiated in 2014 and has since gone through a phased development and review through the groundfish and crab Plan Teams and Scientific and Statistical Committee of the North Pacific Fishery Management Council (NPFMC). Starting in 2017, this framework has been used for three high profile groundfish and crab stocks in Alaska, and three additional applications are underway (Fedewa et al., 2019; Shotwell et al., 2017, 2018, 2019a,b). The framework extracts indicators of hypothesized ecosystem linkages that were formally included in the Alaska Marine ESRs. These indicators are evaluated within an applied stock-specific framework using a consistent statistical method to rank and display the evidence in support of hypothesized relationships. While SAFE chapters have included stock-specific ecosystem considerations for several decades, the new framework provides a standard statistical format for evaluating qualitative inferences about climate impacts on fish and fisheries. To date, the main utility of the ESP framework is its contributions to evaluations of qualitative information to inform adjustments to harvest recommendations that are external to stock assessments (Townsend et al., 2019; Dorn and Zador, 2020). However, stock assessment scientists anticipate that ESPs will accelerate the transition from qualitative evaluations to the integration of time-proven relationships into ecosystem-linked assessments in the future. It is anticipated that by monitoring relationships between key indicators and relevant assessment parameters and functional forms, the benefits of including the relationship to inform the assessment can be evaluated.

[19] Bering Sea Ecosystem Status Report website - https://www.fisheries.noaa.gov/alaska/ecosystems/ecosystem-status-reports-gulf-alaska-bering-sea-and-aleutian-islands

Over the last five years, methods for estimating the effects of fishing on essential fish habitat have improved considerably. Key advancements include the update of the catch-in-areas database (Smeltz et al., 2019) and the application of numerous geospatial statistical tools (GAMS, Maxent, and VAST) to identify and detect explanatory variables that include temperature (Pirtle et al., 2019; Brodie et al., 2020; Goldstein et al., 2020; Rooper et al., 2021). Results facilitate tracking of climate impacts on the distribution of suitable spawning and nursery habitats as well as spatial shifts in post-juvenile distributions.

Through various internal and external funding lines, assessments of the impacts of climate change on Alaska communities have advanced (Seung et al., 2015; Seung and Ianelli, 2016). The Economic SAFE document now includes socio-economic profiles that provide a snapshot of time trends in key indicators of fishery dependent community status. In addition, the Groundfish and Crab Economic SAFEs now include a dashboard to quickly assess time trends in key economic indicators (Fissel et al., 2019). While these have not been formally linked to climate drivers, they serve as a starting point for evaluating mechanisms through which climate drivers impact society.

Ecosystem Status Reports are produced annually to compile and summarize information about the status of the Alaska marine ecosystems for the NPFMC, the scientific community, and the public. To advance ecosystem-based management, scientists must take a broader approach in providing scientific advice to resource managers. The ESRs provide the NPFMC with contextual ecosystem information to inform their annual quota-setting process. The Ecosystem Status Reports of the Groundfish SAFE provide the historical perspective of status and trends of ecosystem components and ecosystem-level attributes using an indicator approach. For the purposes of management, this information must be synthesized to provide a coherent view of the ecosystem effects to clearly recommend precautionary thresholds, if any, required to protect ecosystem integrity. The eventual goal of the synthesis is to provide succinct indicators of current ecosystem conditions and a prognosis of how fish stocks are expected to fare, given concurrent information on ecosystem status. To perform this synthesis, a blend of data analysis and modeling is required annually to assess current ecosystem status in the context of historical and future climate conditions. Ecosystem indicators with hypothesized ecosystem linkages to fish vital rates are then utilized within the ESP framework.

Progress summary
Significant improvements to AFSC's ability to track climate related trends in the eastern Bering Sea have been realized over the last five years. These advancements have been accelerated through internal discretionary and external funding. Many lessons were learned from recent marine heat waves. The marine heat waves revealed the importance of reviewing in-year environmental and socio-economic indicators and the establishment of the Preview of Ecosystem and Economic Conditions (PEEC) meeting ensures this will occur. While scientists within the AFSC have a long history of leadership in the exploration of assessment-relevant ecosystem linkages, the co-occurrence of the NCSS, marine heat waves, climate change, and the establishment of a common statistical framework for evaluating these relationships (i.e., ESPs) has focused new attention on these factors.

Performance relative to reaching these objectives is measured as described below.

- The successful deployment of oceanographic moorings with advanced sensors for monitoring physical and biogeochemical change
- The inclusion of satellite-derived indices of sea ice extent, area, and thickness for use in monitoring changes in environmental conditions
- The successful deployment of advanced technologies for use in monitoring physical, biological, and chemical changes in remote regions of the Bering Sea
- Maintenance of time series included in the (ESRs)
- Bering Sea moorings provide useful indicators of ecosystem trends and are reported in the ESR and PEEC meetings
- Ecosystem indicators are now evaluated mid-way through the calendar year as part of the PEEC meeting
- ESPs have been completed for Alaska sablefish, St. Matthew Island blue king crab, and Bristol Bay red king crab. A draft ESP was completed for Eastern Bering Sea Pacific cod
- To date ecosystem indicators have been transitioned into several eastern Bering Sea assessments:
    - EBS pollock added a multispecies assessment as an appendix to the SAFE
    - EBS Pacific cod added bottom temperature-linked VAST model projections as an index to assess survey catchability
    - Bering Sea Aleutian Islands yellowfin sole includes bottom temperature and mean survey start date as a covariate on survey catchability
    - Alaska sablefish adjusts both the survey and fishery indices for whale depredation within the assessment model and in the calculations of acceptable biological catch.

Understanding Mechanisms (Objective 5)

Goals

Identify the mechanisms of climate effects on ecosystems, living marine resources, and resource-dependent human communities.

- Publish results of Bering Sea Project[20]
- Conduct southeastern Bering Sea ecosystem assessment research on recruitment processes to understand production of key groundfish species
- Conduct Ocean Acidification research[21] on commercially important fish and shellfish species and cold-water corals
- Continue northern fur seal research to assess processes underlying recent declines in overall production
- Conduct ice-associated seal surveys to gain insights into how climate affects these populations

[20] Bering Sea Project website - https://www.nprb.org/bering-sea-project/about-the-project/
[21] AFSC Ocean Acidification research website - https://archive.fisheries.noaa.gov/afsc/HEPR/acidification.php

- Continue passive acoustic surveys for whales to gain insights into how climate affects these populations
- Conduct research on seabird bycatch and use of seabirds as ecosystem indicators
- Study economic effects of climate change
- Project social and human community effects of climate change.

Activities

The scientists at the AFSC have a long legacy of leadership in the study of mechanisms underlying the effects of climate variability and change on marine ecosystems and resource-dependent communities. Internal and external funding has been used to conduct numerous process studies that have been the basis for many of the ecosystem indicators tracked by the AFSC. During the last five years, EcoFOCI (https://www.ecofoci.noaa.gov), a cross-Line Office partnership between AFSC and PMEL, continued its mission to conduct process studies that target Bering Sea walleye pollock, phytoplankton, zooplankton, salmon, and flatfish. These process studies have improved our understanding of mechanisms linking climate drivers to larval or juvenile survival (Wilderbuer et al., 2016; Duffy-Anderson et al., 2017; Hertz et al., 2018, Kimmel et al., 2018; Porter and Ciannelli, 2018; Stabeno and Bell, 2019; Yasumiishi et al., 2019; Yeung and Cooper, 2019; Cooper et al., 2020; Farley et al., 2020). In addition, qualitative network models (QNMs) were used to evaluate management interventions intended to promote the rebuilding of a collapsed stock of blue king crab (*Paralithodes platypus*) around the Pribilof Islands (eastern Bering Sea) (Reum et al., 2020a).

The AFSC developed a cross-divisional research team focused on Pacific cod. This team sought to understand the mechanisms underlying the abrupt onset of marine heat waves and the subsequent collapse of the Gulf of Alaska (GOA) cod stock (Barbeaux et al., 2020) and the marked shift in the spatial distribution of EBS cod (Stevenson and Lauth, 2019). The cod working group completed studies of: cod stock structure (Spies et al., 2020), juvenile cod thermal tolerance (Laurel and Rogers, 2020), and cod movement (Nielsen et al., 2020). The record breaking low ice year also provided new insights into ecosystem responses to abrupt climate change (Duffy-Anderson et al., 2019).

Also, during the last five years, the AFSC Resource Assessment and Conservation Engineering (RACE) Program has continued to use laboratory experiments to evaluate the potential effects of ocean acidification (OA) on federally-managed fish and crab species in Alaska. This work, mostly funded through the NOAA Ocean Acidification Program, is aimed at quantifying OA's physiological effects to predict how fisheries and ecosystems will be affected. In general, fish species in Alaska are relatively resistant to OA (Hurst et al., 2016, 2017; but see Hurst et al., 2019), while crab species are relatively sensitive (Long et al., 2016, 2017, 2019; Meseck et al., 2016, Swiney et al., 2016; Coffey et al., 2017), particularly when OA is combined with increased temperature (Swiney et al., 2017). This work is being used to parameterize stock-assessment models to understand the degree to which individual fisheries and Alaskan coastal communities are vulnerable to OA.

The AFSC Midwater Assessment and Conservation Engineering (MACE) Program deployed four bottom-mounted, upward-looking echo sounder moorings located on the U.S./Russia boundary. In addition to collecting active acoustic data, the moorings were equipped with environmental data sensors through a partnership with PMEL. These moorings were deployed in 2019, and were retrieved in 2020. Data from the moorings will be used to evaluate pollock movement across the U.S.-Russia Convention Line and to examine linkages between migratory behavior and environmental data, results which could provide support for climate-enhanced assessment modeling of EBS pollock.

Focused research on mechanisms underlying northern fur seal foraging have been accelerated through several research partnerships between the Alaska Fisheries Science Center, the Alaska Regional Office, the University of Washington, Innovative Technology for Arctic Exploration, Pacific Marine Environmental Laboratory, and the Lenfest Ocean Program[22]. The bulk of these efforts seek to quantify fur seal behavioral and population responses to their prey through bioenergetic modeling, hindcasting, and deploying innovative technologies such as USVs (Kuhn et al., 2020) and back mounted video cameras. The results from these efforts contribute to fur seal models examining behavioral and population responses to simulated prey fields derived from an end-to-end ecosystem model. In addition, this effort has quantified factors affecting northern fur seal energy expenditures, estimated population level prey consumption, and hindcasted walleye pollock consumption by fur seals to begin coupling a fur seal bioenergetic model with AFSC existing ecosystem and multispecies-stock assessment models (McHuron et al., 2019; McHuron et al., 2020).

Several studies of ice dependent seals were conducted during the last five years. Unoccupied aircraft systems (UAS) have been deployed to understand the impact of loss of sea ice on ice associated seals in the remote arctic (Moreland et al., 2015). Impacts of changing patterns of sea ice extent to the body condition on ice dependent seals have also been examined (Boveng et al., 2020).

Passive acoustic monitoring (PAM) for marine mammals (including pinnipeds and cetaceans) has been ongoing in the Bering Sea via long-term subsurface moorings as well as short-term underway sonobuoy deployments. The mooring work has been funded through a variety of external sources and through continued partnership with PMEL for space on the oceanographic moorings as well as ship time to deploy stand-alone PAM moorings in critical locations. The sonobuoys were donated to AFSC by the Navy, and their deployments have occurred on joint PMEL/AFSC cruises as well as on the International Whaling Commission POWER cruises. The primary focus of the research has been on the critically endangered eastern population of North Pacific right whales (which number in the tens of animals). Results include identification of new call types (Crance et al., 2017), and calling behaviors (Crance et al., 2019) that can be used to track this population, as well as new techniques for distinguishing this species from the acoustically similar bowhead whale (Thode et al., 2017). Data collected have also shown that

[22] Lenfest Ocean Program fur seal project website - https://www.lenfestocean.org/en/news-and-publications/cross-currents/2019/northern-fur-seals-in-the-bering-sea-are-declining-researchers-want-to-know-why

this population is now being detected farther north than in earlier years (Wright et al., 2019), as well as in a high traffic Aleutian Pass (Wright et al., 2018). Changes in the timing of many other marine mammal species, particularly in the northern Bering Sea, have been observed and are currently being prepared for publication. Several studies have utilized Bering Sea AFSC passive acoustic recordings to study other marine mammals including: Frouin-Mouy et al. (2019, ribbon seal), Clark et al. (2015, bowhead whales), and Garland et al. (2015, beluga whales).

Progress summary

Ongoing studies of ecosystem processes in the Bering Sea continue to improve our mechanistic understanding of causal linkages between climate variability and change and ecosystem responses. While this understanding can always be improved, these studies provide the mechanistic understanding of several key ecological linkages necessary for the development of short-term forecasts and long-term projections of the Bering Sea ecosystem for use in short term forecasting and long term climate projections.

Performance relative to reaching these objectives is measured as described below.

- Publication of numerous papers linking ecosystem change to processes underlying production of marine species
- Successful deployment of upward looking sonar and passive acoustic devices for monitoring spatial shifts in fish and marine mammals
- Successful deployment of USVs concurrent with deployment of satellite tags on northern fur seals to assess capture efficiency and foraging behavior
- Successful deployment of UMAs to assess ice-associated seals in remote regions.
- Incorporation of proposed mechanisms in qualitative evaluations (ESPs)

Projecting Future Conditions (Objective 4)

Goals

Identify future states of marine, coastal, and freshwater ecosystems, living marine resources, and resource dependent human communities in a changing climate.

- Ocean model projections. Coupled physical/biological models (ROMS-NPZD) are used to downscale global climate change to the ecology of subarctic regions, and to explore the bottom-up and top-down effects of that change on the spatial structure of subarctic ecosystems
- Incorporate ocean acidification effects into existing ocean models. An ocean acidification module is being added to the coupled physical biological model (ROMS-NPZD)
- Climate-enhanced single-species projection models. Climate-enhanced single-species projection models have been completed for walleye pollock, Pacific cod, arrowtooth flounder, and Bristol Bay red king crab and northern rock sole and provide 20- to 50-year forecasts of their abundance, including a measure of the uncertainty of these forecasts
- Climate vulnerability assessment for the southeastern Bering Sea[23]. A climate vulnerability assessment for the southeastern Bering Sea, which will qualitatively assess

[23] Southeastern Bering Sea climate vulnerability assessment webpage - https://www.fisheries.noaa.gov/data-tools/bering-sea-vulnerability-assessment-species-specific-results

species vulnerabilities to climate change and provide guidance on research prioritization, currently is underway
- Identify human community dependence on LMRs and effects of climate change
- Support Arctic Council and AMAP impacts on coastal communities. The Arctic Monitoring and Assessment Programme (AMAP) of the Arctic Council is preparing a report entitled "Adaptation Actions for a Changing Arctic (AACA)" at the request of the Arctic Council

Activities

Several advancements in seasonal-to-interannual forecasting of the impact of climate variability on marine ecosystems have been realized in the last five years. Through funding provided by the Climate Program Office, seasonal-to-interannual forecasts of Bering Sea ocean temperature and sea ice extent at high spatial and temporal resolutions have been tested with promising results (Jacox et al., 2020) at six month time scales. These coupled ocean-biophysical models have the potential to extend environmental tracking to include hindcasts of phytoplankton and zooplankton bloom timing, distribution, and abundance (Kearney et al., 2020).

In 2015, NOAA funded the Alaska Climate Integrated Modeling project (ACLIM[24], Hollowed et al., 2020). This was a large interdisciplinary, multi-institution, research project that was designed to address long term impacts of climate change on fish, fisheries, and fisheries-dependent communities. The ACLIM framework downscales global climate model projections based on different global greenhouse gas emission scenarios (based on shared socio-economic pathways (SSPs) and representative concentration pathways (RCPs)) to a 10 km resolution, 30 layer coupled regional ocean model that includes carbonate dynamics and nutrient-phytoplankton-zooplankton dynamics (Bering 10k, Hermann et al., 2019; Kearney et al., 2020). Output from the Bering 10k projections of the future of the Bering Sea marine ecosystem are used to drive upper trophic level population dynamic models of various levels of biological complexity including: vulnerability assessments (Spencer et al., 2019), climate enhanced single species models (Spencer et al., 2016), multispecies models (Holsman et al., 2020), food web models (Whitehouse et al., in press), and size spectral models (Reum et al., 2020b). Efforts are underway to include fully coupled end-to-end models this fall.

Progress summary

Considerable progress has been made during the last five years towards objective 4. A substantial 3-year effort to validate short-term (1-9 month) Bering Sea ocean forecasts, using global forecasts from the North American Multi-Model Ensemble to drive a downscaled ocean model of the Bering Sea, is nearing completion. The results will quantify the forecast uncertainty for a range of seasonal starting and end dates. A pilot forecast for summer 2020 Bering Sea bottom temperature was released in April 2020 as part of the Alaska Integrated Ecosystem Assessment Program's PEEC workshop; these results will take on greater importance with the cancellation of bottom trawl surveys in summer 2020. The first operational use of these products (delivery of short-term forecasts to the North Pacific Fisheries Management Council through the Bering Sea ESR and the development of a publicly-accessible

[24] ACLIM website - https://www.fisheries.noaa.gov/alaska/ecosystems/alaska-climate-integrated-modeling-project

website) is scheduled for spring 2021. Further, the use of these short-term ocean forecasts to drive fisheries recruitment models for key species (walleye pollock, Pacific cod, and arrowtooth flounder) is currently being tested.

The recent adoption of the Climate and Fisheries Initiative within NOAA bodes well for the continuation of efforts to conduct and improve climate forecasts and projections.

Performance relative to reaching these objectives is measured as described below.

- Completion of long-term high resolution coupled model projections under multiple emission scenarios
- Completion of long-term projections of future distribution, growth, reproductive potential, and abundance of Bering Sea groundfish and crab
- Incorporation of proposed mechanisms in quantitative models (forecasts and projections)
- Completion of a Bering Sea vulnerability assessment

Informing management (Objectives 1 - 3)

Goals

Identify appropriate, climate-informed reference points for managing LMRs; identify robust strategies for managing LMRs under changing climate conditions; and design adaptive decision processes that can incorporate and respond to changing climate conditions.

- Complete and publish climate-forced single- and multi-species models
- Complete the North Pacific Fishery Management Council, Bering Sea Fishery Ecosystem Plan (FEP)
- Conduct and publish Management Strategy Evaluations (MSEs) to identify harvest control rules that remain effective as climate changes
- Maintain a suite of models designed to provide scenarios of future fish and shellfish production under a variety of climate and fishing scenarios through the Alaska Climate Integrated Project (ACLIM)
- Develop multispecies technical interaction models for use in evaluating management approaches that incorporate an ecosystem approach to fishery management through management of incidental catch and bycatch
- Synthesize information from completed and ongoing regional studies conducted by Japan, the United States, and Norway through the Belmont Forum RAC Arctic project
- Design adaptive decision processes through the development of LK-TK and climate action modules within the FEP

Activities

In accordance with objectives 2 and 3 of the NCSS, the ACLIM modeling suite is being used to design and evaluate the performance of current and alternative management strategies within the context of region-specific projections of anticipated societal responses to changing climate conditions. In Phase 1, the ACLIM project has successfully projected the implications of climate change on the distribution, abundance, and reproductive potential of groundfish and crab and the implications of these changes on fisheries. These projections were used to evaluate the value of EBFM strategies in forestalling climate-induced declines in fish catch (Holsman et al., 2020). Demonstration of an operationalized integrated modeling suite has been achieved through the rapid uptake of updated global climate model output from the Coupled Model Intercomparison Project (CMIP-6) into the ACLIM coupled modeling suite. Through new funding from Coastal Ocean Climate Applications program (COCA), Phase 2 of the ACLIM project will expand this effort to include impacts on marine mammals (northern fur seals) and impacts on fishery-dependent communities.

Objective 1 of the NCSS calls for the identification of climate informed reference points for managing LMRs. In December 2018 the NPFMC approved a Bering Sea Fishery Ecosystem Plan[25] (FEP). The FEP adopted an FEP Climate Module Task Force to provide a conduit for exchanging climate relevant information with fisheries managers. This task force, when coupled with the ACLIM research program, provides a vehicle for developing climate adaptation strategies within an open and inclusive environment, allowing voices from a broad range of stakeholders to be considered in the development of strategic approaches to managing fisheries in a changing climate.

The Belmont Forum RAC Arctic project[26] successfully synthesized the implications of climate change on U.S., Norwegian, and Japanese fish and fisheries. Three synthesis manuscripts are under development for a special theme section in ICES Journal of Marine Sciences (Drinkwater et al., 2021; Mueter et al., 2021; Haynie et al., in prep.).

The NPFMC FEP also established a LK/TK/Subsistence Action Module. This group is exploring protocols for using Local Knowledge (LK) and Traditional Knowledge (TK) in management and understanding impacts of Council decisions on subsistence use. Impacts of actions to adapt to climate change will be explored through ACLIM Phase 2 and will inform the LK/TK/S Action Module.

Progress summary
The NPFMC has adopted an annual Preview of Economic and Ecological Conditions (PEEC) in the early summer prior to the fall evaluation of stock status for groundfish and some crab populations. This preview provides an update on key biological, physical, chemical, and economic indicators that allows early detection of climate driven anomalies. In part, the PEEC meeting was established because early indicators of the implications of the 2015-16 marine heat wave were missed or not fully accounted for by scientists and managers.

Products from the PEEC, the ESR, and the ESPs are used to inform risk tables that document different sources of scientific uncertainty that are external to stock assessments. The short-term forecasts and long-term projections provide the foundation necessary for designing, testing, and implementing climate ready harvest advice. The adoption of the FEP provides a

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[25] Bering Sea Fishery Ecosystem Plan website - https://www.npfmc.org/fishery-ecosystem-plan-team/
[26] Belmont Forum Arctic projects website - https://www.belmontforum.org/archives/projects/resilience-and-adaptive-capacity-of-arctic-marine-systems-under-a-changing-climate

forum for inclusive participatory decision making with respect to fisheries management in the future.

Solidifying the funding for the ACLIM modeling suite would provide continuity within the program going forward. Pairing FTEs with continued research opportunities, the approach currently used for the EcoFOCI program and the approach recommended for the Climate and Fisheries Initiative (CFI), is recommended for ACLIM as well.

Performance relative to reaching these objectives is measured as described below.

- Completion of comparative testing of the performance of current and alternative harvest strategies for managing groundfish and crab under a changing climate
- Demonstration of the operationalization of the ACLIM modeling suite
- Establishment of an open forum for discussion of current and alternative management strategies under a changing climate through FEP action modules

4.3 Conclusions

Thoughts on what went well and lessons learned.
The combination of strategically directed opportunity funds that accelerated research, the emergence of abrupt climate events (e.g., marine heatwaves and storms), growing evidence of changing climate on the world's oceans (USGCRP, 2018; Pörtner, 2019) and the recognition of the importance of the ocean in the 17 United Nations Sustainable Development Goals made the NCSS a highly relevant strategic planning document. The NCSS provided much needed guidance and structure for the design and implementation of AFSC's climate science research enterprise. It provided clear goals and objectives that allowed AFSC's interdisciplinary research teams to clearly understand how products of their research would contribute to the larger goals of providing climate informed harvest strategies and climate ready harvest control rules.

The periodic release of large and small funding opportunities worked very well. Small funding opportunities within the RAP regions maintained interest in the program and the supplemental funding leveraged larger projects. The larger funding opportunities allowed NMFS to leap forward in its knowledge and capabilities across all seven strategic goals. In particular, the release of multi-year funding from internal and external funds from programs such as NPCREP, FATE, RTAP, NPRB (including the Bering Sea Project), NFS, Lenfest, and COCA were very valuable. These opportunity funds allowed the development of fully coupled climate to fish and fisheries models for short-term forecasts and longer-term projections of the future productivity of the Bering Sea.

Monthly meetings with RAP teams improved communication and collaboration between NMFS/OAR research teams. Many RAP team members were highly involved in the planning and execution of the 4th Effects of Climate Change on the World's Oceans meeting in 2018. This gathering of scientists from across the world in the U.S., mid-way through the first five years of the NCSS, was very fortuitous as it provided in-person communication of research ideas and products across the regions.

Recognition of the global, national, and regional importance of climate change research contributed to the development of NOAA's Climate and Fisheries Initiative which outlines how NOAA will deliver next-generation high resolution ocean simulations for use across all of NOAA.

Potential considerations for a RAP 2.0

Future focal areas - A particular focus on developing a permanent infrastructure for quantitative forecasting and climate projections should be a key focus of RAP 2.0. Planning for this effort has already started as part of the Climate and Fisheries Initiative which will provide hindcasts, nowcasts, S2D forecasts, and decadal to century scale projections of ocean conditions using state of the art high resolution ocean models (MOM6). Efforts to provide clear on-ramps to inform fisheries management through RAP 2.0 is a clear and tangible goal.

Metrics and milestones to consider - Follow a similar approach used for the annual Progress and Plans reports and spreadsheet in terms of aiming to provide readers (leadership, partners) with pertinent information that highlights what progress has been made and what is left to accomplish.

Table 4.2 highlights some of the key RAP achievements.

Table 4.2. A selection of EBS RAP activities organized by NCSS Objective.

Informing Management (NCSS Obj. 1 – 3) • Adoption by the NPFMC of a Bering Sea Fisheries Ecosystem Plan (FEP) • Evaluation of EBFM strategies in forestalling climate induced declines in catch using the ACLIM framework
Understanding Mechanisms and Projecting Future Conditions (NCSS Obj. 4 & 5) • Validation of short-term Bering Sea ocean forecasts • Development of the ACLIM framework • Climate vulnerability assessment for the southeastern Bering Sea • Conduct ocean acidification research on commercially important species • Conduct process studies on pollock, zooplankton, phytoplankton, salmon, etc.
Infrastructure and Tracking Change (NCSS Obj. 6 & 7) • Maintain research capabilities, including food habits, genetics, behavioral ecology, etc. • Maintain standard ecosystem monitoring • Ecosystems Status Report and IEA • Use of advanced technologies (UxS) to expand survey capability

4.4 Acknowledgements

Chairs past and present: Mike Sigler (2015-2017) and Anne Hollowed (2018-Present)

Current Members:
PMEL: Phyllis Stabeno and Carol Ladd
AFSC: Janet Duffy-Anderson (fisheries oceanography), Alan Haynie (economics), Jeremy Sterling (marine mammals), Ed Farley (salmon), Kerim Aydin (ecosystems), Kirstin Holsman (ecosystems/bioenergetics), James Thorson (habitat and EFH), Kalei Shotwell (stock assessments and ESPs)

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5. Gulf of Alaska Regional Action Plan

5.1 Introduction

A working group consisting of representatives from the Alaska Fisheries Science Center (AFSC), the Alaska Regional Office, and the Pacific Marine Environmental Laboratory (PMEL) was formed in 2017 (see Section 5.4 for list of members). The working group, chaired by Martin Dorn, met several times to review previous climate research in the Gulf of Alaska (GOA), guidance documents, and the Regional Action Plans (RAPs) being developed for other regions. A draft RAP was prepared by summer of 2017, which was then reviewed internally, and by advisory bodies of the North Pacific Fisheries Management Council, including the Gulf of Alaska Groundfish Plan Team and the Scientific and Statistical Committee. The draft RAP was presented to the Council in February 2018. A technical memorandum describing the RAP was published in April 2018. The GOA RAP was designed as an integrated program organized around monitoring, process studies, risk assessment, and modeling.

The first year of implementation of the RAP was 2018. Although substantial progress has been made on some of the activities described in the Gulf of Alaska RAP, the timing at present is not ideal for a review and synthesis. Many of the activities listed in the RAP are just beginning, and others are scheduled to start in early 2021. However, in the interest of supporting the effort to compile a national synthesis of progress on the RAPs, we provide here information on progress towards achieving the National Climate Science Strategy (NCSS) goals. The activities are organized by the seven NCSS objectives (7—Build, 6—Track, 5—Understand, 4—Project, 1-3—Inform). Many of the research activities that we describe span several of the NCSS objectives, and therefore we have assigned each activity into a NCSS objective according to its predominant role. Reformulating the NCSS objectives in a more appropriate and actionable framework is a recommendation of the GOA RAP working group.

5.2 Activities and Progress

Build and Maintain Infrastructure (Objective 7)

Goal
Build and maintain the science infrastructure needed to fulfill NOAA Fisheries mandates under changing climate conditions.

Activities
Ecosystem monitoring surveys. Tracking changes in the GOA ecosystem relies on an extensive set of surveys that regularly monitor the distribution and abundance of managed species and the environmental conditions in the Gulf of Alaska. These surveys continued as scheduled in 2018 and 2019, and included acoustic surveys of pre-spawning pollock in Shelikof Strait and other localities (Lauffenburger et al,. 2019; Stienessen et al., 2019), a sablefish longline survey (Malecha et al., 2019), the gulf-wide NMFS bottom trawl survey (Raring and von Szalay, in prep.), a bottom trawl survey by ADF&G, a summer acoustic-trawl survey (Jones et al. in prep.),

Southeast Alaska coastal monitoring, and a survey of Steller sea lions by airplane and chartered vessel. EcoFOCI led two ecosystem surveys in the GOA, a spring ichthyoplankton survey, continuing a 35+ year time-series (begun in 1984) of fish early life stages, and a summer young-of-year groundfish survey continuing a 20+ year time-series (begun in 2001). Both surveys included collections of phytoplankton and zooplankton and well as physical oceanographic observations. Monitoring and process surveys conducted by AFSC and its partners in the Gulf of Alaska are the foundation for research into impacts of climate change and science-based management of the resources in the region.

A survey of pre-spawning pollock in Shelikof Strait was completed in late winter of 2020 immediately prior to the nationwide shutdown of NOAA activities due to the coronavirus outbreak (McCarthy et al., in prep.).

Oceanographic moorings. There has been a long-term (1999 - present) oceanographic mooring maintained by PMEL in Woman's Bay, Kodiak Island. However, it was generally recognized that this was an inadequate level of monitoring given the size and complexity of the Gulf of Alaska. On September 30, 2019, PMEL deployed an additional mooring in the Shumagin Islands. In addition, a passive acoustic recorder was deployed at the site. Though not funded by RAP, this mooring adds value to the marine mammal database of acoustic observations. An additional mooring was deployed at Cross Sound in the eastern Gulf of Alaska in winter of 2020 using funding from NMFS headquarters to support the RAPs. Temperature and salinity will be measured in the inflow region and currents (75kHz) will be measured throughout the water column.

Additional ecosystem moorings in the Gulf of Alaska are needed to continuously track oceanographic and ecosystem properties. Finding a mechanism to ensure funding for current PMEL moorings and additional moorings is a high priority.

Funding from headquarters to support RAPs was used to purchase oceanographic equipment to deploy on the NMFS summer bottom trawl survey to better monitor ocean acidification and dissolved oxygen. The initial purchase was later augmented by AFSC funds to provide two CTDs (conductivity temperature depth) for each survey vessel that will expand on the temperature trends already reported GOA-wide to the Ecosystem SAFE Chapter.

Northern Gulf of Alaska Long-Term Ecological Research study area. The Long-Term Ecological Research (LTER) network was created by the National Science Foundation in 1980 to conduct research on ecological issues that can last decades and span huge geographical areas. A group of researchers led by scientists from University of Alaska Fairbanks were awarded a grant to establish an LTER site in the northern GOA. This is an integrated research program that builds upon and enhances the Seward Line time series, in addition to adding three new sampling lines located upstream (Cape Suckling and Middleton Island) and downstream (Kodiak Island) of the Seward Line. It includes spring, summer, and fall field cruises and a new (2019) mooring, the Gulf Ecosystem Observatory (GEO) on the outer shelf adjacent to the Seward Line, in addition to the GAK1 mooring with a 50 year time series (1970) on the inner shelf. Other components of the program are process studies that focus on mechanisms leading to variability in GOA productivity, and modeling studies to predict ecosystem responses to projected environmental changes. The LTER in the Northern GOA became operational in 2018.

Collaborations between the LTER Program and the EcoFOCI program extend zoo- and ichthyoplankton observations for the Gulf of Alaska.

Gulf Watch Alaska. Gulf Watch Alaska (GWA) is the long-term ecosystem monitoring program of the Exxon Valdez Oil Spill Trustee Council. GWA is an anticipated 20-year program that was initiated in 2012, and includes annual ecosystem sampling in the GOA with most sampling occurring from Cape Suckling to Cook Inlet. GWA includes over 25 principal investigators from multiple agencies, universities, and research organizations, but the program and science lead is through AFSC. GWA has three main research and monitoring components: 1) environmental drivers (physical and biological oceanography); 2) pelagic ecology (prey and upper trophic level species; and 3) nearshore ecology (coastal and intertidal ecosystems). There are 11 field sampling projects within GWA. These projects include many biophysical time series extending decades, with the longest over 40-years (e.g., hydrographic sampling at GAK-1 and in Prince William Sound). Eighteen GWA-supported time series are now included annually in NOAA's ecosystem considerations report to the NPFMC. The development of additional ecosystem indicators is being investigated, as are contributions to Ecosystem and Socioeconomic Profiles (currently for sablefish).

Progress summary
By and large, NOAA has met its goal of maintaining and expanding its capacity for tracking changes in the Gulf of Alaska ecosystem. Maintaining the current suite of surveys is an increasing challenge in a period of flat or declining funding. A 5th vessel is needed to complete the full suite of AFSC bottom trawl surveys in any given year. AFSC currently only has funding for four vessels, which may result in a 2-vessel (vs. 3-vessel) survey and thus reduced sampling density in the Gulf of Alaska. Ecosystem surveys remain underfunded and are needed to provide cross-trophic metrics. Expansions in capacity include new ecosystem moorings, new oceanographic equipment to track climate change, and the new LTER study area in the Northern GOA. There is a critical need to maintain and expand the ecosystem moorings in the Gulf of Alaska. Finding a mechanism to ensure long-term funding for these moorings is a high priority. The monitoring activities by partners, such as the Northern Gulf of Alaska LTER, and the Gulf Watch Alaska program, provide a valuable addition to the monitoring done by NOAA, and further development of these partnerships is a priority.

Tracking Change (Objective 6)

Goal
Track trends in ecosystems, living marine resources (LMRs), and LMR-dependent human communities and provide early warning of change.

Activities
Annual ecosystem status report. An Ecosystem Status Report for the Gulf of Alaska was produced annually to compile and summarize information about the status of the ecosystem for the North Pacific Fishery Management Council, the scientific community, and the public. These reports include ecosystem report cards, ecosystem assessments, and ecosystem indicators that together provide context for ecosystem-based fisheries management in Alaska.

New time-series indicators of thermal conditions in the Gulf of Alaska. This project was funded by RAP funds from headquarters. In FY18, this project reprocessed and compiled historical oceanographic data from 99 EcoFOCI cruises into a standardized format to improve data accessibility. The historical data have since been incorporated into multiple manuscripts (e.g. Rogers et al., 2020). An R package was developed to aid in processing data at sea and for producing standardized products (maps, time-series) of relevant oceanographic properties. These products are now available immediately after surveys, thus facilitating their incorporation into stock and ecosystem assessments, presentations to plan teams and the NPFMC, research studies, and IEAs.

Socioeconomic monitoring of Alaska fishing communities. Through various internal and external funding lines, assessments of the impacts of climate change on Alaska communities have advanced (Seung et al., 2015; Seung and Ianelli, 2016). The Economic SAFE document now includes socio-economic profiles that provide a snapshot of time trends in key indicators of fishery dependent community status (Economic SAFE[27], Community Snapshots[28]). In addition, the Groundfish and Crab Economic SAFEs now include a dashboard to quickly assess time trends in key economic indicators (Fissel et al., 2019). While these have not been formally linked to climate drivers, they serve as a baseline for evaluating mechanisms through which climate drivers impact society.

Advances in Gulf of Alaska nearshore habitat science. Recent work has advanced assessment of Essential Fish Habitat in the Gulf of Alaska in nearshore areas by combining shoreline habitat information from the Alaska *ShoreZone* dataset with the AFSC's Nearshore Fish Atlas (Grüss et al., 2021). Results will support understanding of how climate-induced changes in shoreline habitat, such as eelgrass and kelp, may affect early life stages of federally managed species.

Spring Preview of Ecosystem and Economic Conditions (Spring PEEC). In order to provide rapid "early warnings" of ecosystem conditions as they developed, in 2019 and 2020 AFSC convened a "Spring Preview of Ecosystem and Economic Conditions (PEEC)", wherein programs presented survey and model results of current environmental conditions in Alaska marine waters. Development of on-board rapid assessments (e.g., for zooplankton and larval fish) allowed for field observations to be provided in near real-time, documenting ecological responses to changes in the environment. The 2019 PEEC indicated a return of warm conditions in the GOA, similar to the marine heatwave years of 2014-2016. The new warm event continued through the summer, and updated physical and biological observations were presented to the NPFMC in October 2019, as "Early Warnings" ahead of the TAC-setting process for groundfish. This represents a significant advancement in the speed and efficiency with which ecosystem information is available for informing management advice, and lays the groundwork for not only monitoring, but also responding to rapid changes in climate. The positive reception of the PEEC resulted in this workshop becoming an annual meeting (with support from the Alaska IEA Program) in the North Pacific assessment and management process.

Ecosystem and Socioeconomic Profile. A new framework, termed the Ecosystem and Socioeconomic Profile (ESP), has been developed for operationalizing the integration of

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[27] Economic SAFE reports website - https://www.fisheries.noaa.gov/alaska/ecosystems/economic-status-reports-gulf-alaska-and-bering-sea-aleutian-islands
[28] Alaska community snapshots website - https://archive.fisheries.noaa.gov/afsc/REFM/Socioeconomics/Projects/communitysnapshots/fullmap.php

ecosystem and socioeconomic factors with NOAA Fisheries' stock assessment system (Shotwell et al., in prep.). The approach builds on the century-long legacy of qualitative reviews, conceptual modeling, and retrospective studies focused on detecting mechanisms underlying ecosystem responses to improve stock assessments. The ESPs are designed to identify, test, and vet the ecosystem process linkages within the scientific review process. As such, the ESP presents and communicates the emerging evidence linking ecosystem processes to stock assessments and assists with transitioning to ecosystem-linked next generation stock assessments. The framework includes four main steps: 1) a focusing effort to understand the data availability for each stock and develop a list of priority stocks for producing ESPs; 2) a grading exercise evaluating both a standard set of stock metrics and processes driving stock dynamics to identify the relationships with stock assessment parameters; 3) defining a suite of indicators to monitor and analyze trends for these indicators using consistent statistical tests to rank and display evidence in support of the hypothesized relationships; and 4) creating a standardized reporting template that is concise and conveys the status of the leading indicators to fisheries managers.

The ESP process was initiated in 2014 and has since gone through a phased development and review through the groundfish and crab Plan Teams and the Scientific and Statistical Committee of the NPFMC (Shotwell, 2018). Starting in 2017, this framework has been used for three high profile groundfish and crab stocks in Alaska, and three additional applications are underway (Shotwell et al., 2017, 2018, 2019a,b; Fedewa et al., 2019). While SAFE chapters have included stock-specific ecosystem considerations for several decades, the new framework provides a standard statistical format for evaluating qualitative inferences about climate impacts on fish and fisheries. To date, the main utility of the ESP framework is its contributions to evaluations of qualitative information to inform adjustments to harvest recommendations that are external to stock assessments (Townsend et al., 2019; Dorn and Zador, 2020). A series of three workshops are scheduled to improve the development of the ESPs at the AFSC (2019-2021) and accelerate the transition from qualitative evaluations to time proven ecosystem-linked assessments. These three workshops will aim to improve ecosystem and socioeconomic data accessibility, increase integration of indicators into assessment models, and provide relevant advice to fisheries managers in a timely and efficient manner.

Progress summary

There have been significant improvements to AFSC's ability to track climate related trends in the Gulf of Alaska over the last several years. The development of ESPs, the PEEC workshops, and continued refinement of the Ecosystem Status Report provide a comprehensive evaluation of current environmental and ecosystem conditions that can be considered in the annual NPFMC fisheries management process. Risk tables are now used in stock assessment to synthesize information on assessment uncertainty, population dynamics, environmental/ecosystem considerations, and fishery performance (Dorn and Zador, 2020), thus ensuring that management actions are responsive to rapidly changing conditions. These advancements have been accelerated through internal discretionary funding and external funding. While scientists within the AFSC have a long history of leadership in the exploration of assessment relevant ecosystem linkages, the co-occurrence of the NCSS, marine heatwaves, climate change, and the establishment of a common analytical framework for evaluating these relationships (i.e., ESPs and risk tables) has focused new attention on these factors.

Understanding Mechanisms (Objective 5)

Goal
Identify the mechanisms of climate effects on ecosystems, living marine resources, and resource-dependent human communities.

Activities
Process studies of ocean acidification and temperature impacts on marine species in the Gulf of Alaska. In FY2018, two experiments were performed examining the sensitivity of walleye pollock to elevated CO_2 levels associated with ongoing ocean acidification (OA). Following-up on earlier experiments, the experiments examined the sensitivity of walleye pollock eggs and larvae to elevated CO_2. This experiment compared the offspring of "wild" fish captured on spawning grounds in the Gulf of Alaska to offspring from a laboratory-maintained broodstock. In collaboration with colleagues from Oregon State University, samples were analyzed for potential OA-induced developmental anomalies and lipid deficiencies. In a separate experiment, the impacts of elevated CO_2 on the schooling behavior of juvenile walleye pollock were examined. Elevated CO_2 has been shown to disrupt aspects of behavior in a number of fish species. Manuscripts describing both the physiological and behavioral responses of walleye pollock to OA are in development.

In FY2019, an experiment was conducted to examine the interactive effects of high CO_2 and prey nutritional quality to first-feeding northern rock sole larvae. Fish were reared from eggs of a laboratory-maintained broodstock and reared for one month after hatching. This work was conducted in collaboration with colleagues from Oregon State University. In separate experiments, thermal impacts on growth rates of yellowfin sole was examined. In one experiment, age-0 fish were captured from Kodiak Island nursery grounds and transported to the laboratory. Growth rates were measured over six weeks at temperatures from 2-16°. In another experiment, eggs were collected from spawning activity of a newly-established broodstock of yellowfin sole. The effect of temperature on incubation time and size at hatch were examined. Analyses of these experiments are currently underway and a follow-up experiment with yellowfin sole larvae is planned for FY21.

Spatial response of northeast Pacific groundfish to anomalous warming in 2015. This project examined the role of extreme environmental conditions in 2015 on the spatial distribution patterns of northeast Pacific groundfish throughout their range. The project utilized the alignment of multiple summer survey efforts encompassing stations along the US west coast, the Canadian Coast and the western Gulf of Alaska (GOA Bottom Trawl Survey) to compare groundfish responses to warming ocean conditions. This project ended in FY18 and publications resulting from this project began to appear in FY19 (Blake et al., in press; Li et al., 2019; Yang et al., 2019; Hinckley et. al., 2019; Li et al., in review; Barbeaux et al., 2020). Other synthesis papers looking at impacts of the heatwave on a broader range of ecosystem components have recently been published or are in review (Litzow et al., 2020; Suryan et al., 2021).

Pacific cod recruitment and the environment. In addition, the AFSC developed a cross-divisional research team focused on Pacific cod. This team sought to understand the mechanisms underlying the abrupt onset of marine heatwaves and the subsequent collapse of the GOA cod stock and the marked shift in the spatial distribution of EBS cod. The cod working group completed studies of: cod stock structure (Spies et al., 2020), thermal tolerance of eggs (Laurel and Rogers, 2020), and cod movement (Nielsen et al., 2020). The record breaking low ice year also provided new insights into ecosystem responses to abrupt climate change (Duffy-Anderson et al., 2019).

Multiple efforts were made in FY19 to address how climate is impacting recruitment dynamics of Pacific cod in the Gulf Alaska, including two age-0 cod field surveys, an archival sample analysis, and a modeling effort that resulted in a peer-reviewed publication. Survey 1 extended the time series of the Kodiak beach seine survey (2006-present) targeting summer 0-group gadids in nearshore regions of Kodiak from mid-July through late August. Survey 2 was a spatially expanded survey using identical gear that was supported by the NOAA Cooperative Research project "Understanding post-settlement survival for juvenile Pacific cod in the Gulf of Alaska (Year 2)". Both Survey 1 and Survey 2 indicated nearly 2 orders of magnitude less CPUE of age-0 cod than 2017 and 2018. Environmental conditions and CPUE were very similar to observations observed during the 2014-16 marine heatwave. Finally, a peer-reviewed manuscript (Laurel and Rogers, 2020) was published that described how climatic warming is likely leading to loss of Pacific cod spawning habitat in the Gulf of Alaska.

Recruitment processes. Diverse projects in FY18 - FY20 investigated climate effects on early life stages of fishes and their prey, providing new mechanistic understanding and refined parameters for modeling climate impacts on fish and fisheries. The marine heatwave of 2014-2016 provided a natural experiment for studying ecological impacts of warming, including a broad assessment of impacts of the heatwave on larval fishes in the GOA and California Current (Nielsen et al., in press), and an in-depth study of heatwave impacts on GOA pollock through their first year of life (Rogers et al., 2020). Historical and ongoing EcoFOCI collections enabled an analysis of pollock spawn timing, finding significant phenological shifts with temperature and spawner age structure (Rogers and Dougherty, 2019). Spring and summer winds were found to shape age-0 pollock spatial distributions and eventual recruitment success (Wilson and Laman, 2020). Additional studies included an analysis of historical zooplankton community dynamics and responses to environmental forcing (Kimmel and Duffy-Anderson, 2020), a study of the effects of temperature on the density and distribution of capelin (McGowan et al., 2019), and an analysis of the role of eddies for transport and recruitment of arrowtooth flounder (Goldstein et al., 2020). For sablefish, a thermal threshold was identified during early development (yolk-sac stage) that has contributed to an EFH project using individual-based models to estimate habitat-related survival rates. Ongoing work is assessing variation in connectivity for halibut between the GOA and EBS in warm and cold years. The Recruitment Processes Alliance is developing their 5-year strategic plan which includes identifying research priorities to support the GOA RAP.

Initial phase of the Gulf of Alaska Integrated Ecosystem Assessment. A place-based IEA was established in Sitka, Alaska to identify information needs and empower coastal community members in addressing management concerns. The first stage of the IEA loop was completed, including the following steps: 1) scoping of the project (definition of a spatiotemporal scale and focal species); 2) identification of local ecosystem components and threats; and 3) conceptualization of the local ecosystem. Public workshops focused on ecosystem processes, ecosystem services, and local ecological knowledge were held to identify user-defined products and co-develop indicators for the IEA. Products from this effort include a set of regionally-distinct conceptual models representing the eastern GOA ecosystem, a dynamic qualitative network model, and ecosystem indicators. They also include a catalog of data sources on biological and physical trends, Shiny Apps, and a webpage.

Specific deliverables include a research paper on explaining the development of co-produced conceptual models (Rosellon-Druker et al., 2019) and a manuscript describing how well-being is derived from local fisheries that includes the development of 10 human dimensions indicators (Szymkowiak and Kasperski, 2021). Other deliverables include a Shiny App that displays the location of rare species captured in commercial fisheries and an operationalized conceptual model for sablefish using a qualitative network model framework that demonstrates how our understanding of the marine ecosystem, including alternative plausible future scenarios (e.g., climate change, continued recovery of whale populations) that were developed in the GOA IEA process, can be applied to fishery management to promote decision-making to ensure sustainability of all species and the wellbeing of community stakeholders.

Progress summary
There have been significant improvements to AFSC's ability to identify the mechanisms of climate effects on the Gulf of Alaska ecosystem and living marine resources. AFSC has a strong OA program that is conducting increasingly sophisticated experiments on the dual effects of OA and ocean warming on fish development and mortality. In response to the marine heatwave in the GOA during 2013-2016 and the associated decline in Pacific cod abundance, several multi-faceted studies were initiated to gain a better understanding of the effect of these extreme events on marine biota, with a particular focus on Pacific cod. AFSC's recruitment process group continues to do important research on the environmental forcing of early life history. Finally, the initial progress to develop place-based IEAs in the GOA reinforces the RAP's focus on impacts to fishery-dependent communities in the GOA. We are continuing to develop IEA products for the community of Sitka, Alaska and planning on initiating a place-based IEA for Kodiak, Alaska.

Projecting Future Conditions (Objective 4)

Goal
Identify future states of marine, coastal, and freshwater ecosystems, living marine resources, and resource dependent human communities in a changing climate.

Activities
ROMS/NPZ modeling in the Gulf of Alaska. Work has begun on a recently funded project for ROMS/NPZ modeling that will produce high-resolution projections of coupled ocean atmosphere conditions under two climate scenarios for the period 2006 to 2100. The fine spatial grid of the model will capture important regional features, such as the Alaska Coastal Current in the GOA. Funding for this project is supported by several successful proposals that will allow a continuous set of projections to be run for the historical period up to the present, and for projections during the period 2006 to 2100. These projections will provide critical input to Management Strategy Evaluations and ecosystem models to evaluate impacts on marine populations, ecosystems, and fishing communities in the GOA.

Climate-forced multi-species models. The climate-enhanced multi-species assessment model (CEATTLE) for the GOA has been successfully transferred to the R-based TMB modeling platform. The model is further being revised to include additional bottom-up climate-driven effects on growth and mortality. As part of this work, refinements to the bioenergetics model for Pacific cod were completed and include updated temperature functions that predict consumption, respiration, and growth. These functions were also applied to diet data for the GOA to produce bioenergetic indicators of changes in trophic dynamics over time that will be included in the GOA Ecosystem Status Report. Work on the CEATTLE model for the GOA progressed in FY19. Consistent performance was found between CEATTLE and the primary stock assessments when CEATTLE is run in single species mode. Diet data are now being fit in the model rather than used deterministically. This research has been presented to the GOA plan team for the NPFMC in 2018 and 2019. The NPFMC SSC was supportive of the research, and encouraged comparison between multi-species models and enhanced single-species models.

Climate-enhanced single species modeling. A project to develop a flexible projection modeling tool to evaluate environmental forcing under climate variation is just starting. The projection model will address the research goal of developing climate-forced single species models (CC-SSM) in the GOA RAP. A sex- and age-structured stock projection model will be used to project the dynamics of North Pacific groundfish stocks in tiers 1-3 in the NPFMC tier system, and incorporate environmental forcing on life history parameters, mortality, and recruitment. The model will be applied to stocks identified as priorities for MSE in the GOA Climate Regional Action Plan. ROMS/NPZ projections will be utilized to evaluate climate change impacts. The model is intended to be used routinely by assessment scientists to provide information to managers and stakeholders on likely climate impacts on groundfish in the North Pacific.

Vulnerability analysis for GOA fisheries resources. Planning for this project is going on now since ROMS/NPZ projections will be available from the present to 2100 using selected Earth System Models from CMIP6. Work will likely begin in FY21 and will require 1-2 years.

Progress summary

The projects under this objective are still in progress with varying degrees of completion. There is a reasonable expectation that results will be available in the next 1-2 years. Together these projects form a strong contribution to the challenge of projecting future states of the Gulf of Alaska ecosystem, and assessing impacts on marine resources and fishery-dependent communities. Looking forward, additional modeling approaches are needed to address a broader spectrum of ecosystem issues, and stronger coupling of ecological and socioeconomic models is needed to project future conditions and socioeconomic impacts.

Informing management (Objective 1-3)

Goals

Identify appropriate, climate-informed reference points for managing LMRs; identify robust strategies for managing LMRs under changing climate conditions; and design adaptive decision processes that can incorporate and respond to changing climate conditions.

Activities

The GOA RAP is designed to be an integrated program that includes conducting quantitative risk assessments and management strategy evaluations for commercially important species, and assess potential changes in ecosystem productivity. There also is a strong focus on projecting community-level social and economic impacts of climate change to assist these communities in adapting to change. However, the RAP received very modest amounts of dedicated funding, and other internal funding sources and staffing at AFSC were not available to initiate a strong modeling effort. However, recently AFSC, in collaboration with the University of Washington, received awards from the North Pacific Research Board and NOAA's Coastal and Ocean Climate Applications (COCA) program to move forward with a robust modeling effort in the GOA to address NCSS objectives 1-3. This project will involve a multi-model approach including the development of regional Ecopath models and an Atlantis ecosystem model for the GOA. The project includes a fleet dynamics component, a marine mammal project looking at heatwave impacts on Steller sea lions, a sociological study of adaptive capacity in fishing communities in the GOA, and coupled regional economic models for southwest Alaska. This research intends to evaluate the suitability of the Optimum Yield (OY) range for the Gulf of Alaska and the biological reference points used for status determination of individual stocks under projected climate scenarios. It will also evaluate climate impacts on fishing communities in the GOA using coupled ecological and economics models. This research has a three-year timeline starting in FY20, so results will not be available for several years.

5.3 Conclusions

By and large, the progress under the GOA RAP seemed reasonable given that we are approximately two and a half years into a five-year work plan. Progress is heavily dependent on external funding rather than being part of the core mission of AFSC. Supporting these projects with external funding should be regarded as an interim solution since there is a continuing need for both ROMS and ecosystem modeling capacity at AFSC, both to assess climate change impacts and to address other ecosystem-based fisheries management issues. This shortfall in capacity ideally would be addressed by creating dedicated positions within AFSC or PMEL staff. Access to and support for additional computing and storage capacity will be required to run and archive these computationally intensive models.

Specific research projects that merit consideration in the next planning exercise include:

- Adding size spectrum models to the multi-model ensemble to provide a comparison to EBS size spectrum models
- Including additional ESM climate projections to the suite of climate projection. This will allow more comprehensive evaluation of uncertainty in climate projections
- Adding communities to those borough and census areas already included in the computable general equilibrium regional economic model. This would allow contrasts to be made between climate impacts on resource-dependent communities and impacts on communities in the northern GOA and in Southeast Alaska whose economies depend more on tourism

It should be noted that these recommendations involve relatively incremental additions to current projects. A concerted effort to produce the next iteration of the RAP should allow itself a wide scope of potential research activities.

Table 5.1 highlights key Gulf of Alaska RAP accomplishments.

Table 5.1. A selection of Gulf of Alaska RAP accomplishments grouped by NCSS objective.

Informing Management (NCSS Obj. 1 – 3)
• Starting development of a multi-model framework to evaluate OY range and biological reference points under projected climate scenarios
Understanding Mechanisms and Projecting Future Conditions (NCSS Obj. 4 & 5)
• Improved understanding of marine heatwaves on northeast Pacific groundfish and Pacific cod • Development of the initial phase of place-based IEA for Sitka, AK, including conceptual models and ecosystem indicators
Infrastructure and Tracking Change (NCSS Obj. 6 & 7)
• Annual ecosystem status reports • Early warnings of ecosystem and economic conditions through the "Spring PEEC" workshops • Development of the Ecosystem and Socioeconomic Profiles (ESPs) framework • Ecosystem monitoring surveys and expansion of sampling capabilities on moorings

5.4 Acknowledgements

Gulf of Alaska Working Group Members
Chair: Martin Dorn
AFSC members: Curry Cunningham (management strategy evaluation), Michael Dalton (economics), Brian Fadely (marine mammals), Anne Hollowed (stock assessment and IPCC), Kirstin Holsman (ecosystems and bioenergetics and IPCC), Jamal Moss (ecosystem monitoring), Olav Ormseth (GOA IERP), Wayne Palsson (groundfish assessment), Patrick Ressler (midwater acoustic assessment), Lauren Rogers (recruitment processes), Mike Sigler (habitat and ecological processes), and Marysia Szymkowiak (sociology)
PMEL members: Phyllis Stabeno (physical oceanography)
Alaska Regional Office members: Brandee Gerke (protected resources)

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6. The Western Regional Action Plan

6.1 Introduction

The Western Regional Action Plan (WRAP) provides the framework to coordinate efforts between the Northwest Fisheries Science Center (NWFSC) and the Southwest Fisheries Science Center (SWFSC) (collectively the Centers), with participation of the West Coast Regional Office (WCRO), to increase and organize the production, delivery, and use of climate-related information to accommodate the National Marine Fisheries Services (NMFS or NOAA Fisheries) climate-related information needs for managing marine resources in the California Current Large Marine Ecosystem (CCLME). The WRAP was adopted in 2016 as the west coast implementation of the national framework laid out in the Fisheries Climate Science Strategy (NCSS).

The NCSS and the WRAP contain seven interdependent climate science strategic objectives supporting the ultimate goal of providing climate-informed management reference points. Over the last five years, the Centers have continued to develop the tools necessary for understanding the elements that go into including climate and other ecosystem considerations in fisheries management actions.

The seven objectives start with identifying and collecting the information necessary for monitoring the ecosystem. This information in turn allows understanding of change and how to track environmental changes. That understanding leads to information necessary for sustainable management decisions.

This five-year summary and Progress Report is organized around the seven objectives, with synthesis included at the end. We start at the base of the “pyramid of objectives”, data and science infrastructure, and work up through the seven objectives for managing living marine resources. Table 6.1 summarizes key accomplishments, grouped by NCSS objectives.

During this five year period, there have been two significant ecosystem events impacting the eastern Pacific: the 2014-2016 Marine Heat Wave and the 2020 COVID-19 coronavirus pandemic. The Marine Heat Wave, colloquially known as “the blob”, provided a stress test on what future climate change conditions could be, and the COVID-19 pandemic caused the cancellation of most of the 2020 summer field work and survey cruises. How we adapt these serious ecosystem challenges to the WRAP process and modify “business as usual” will create new management stresses that will require significant rethinking of how we manage our fishery resources.

Table 6.1. A selection of WRAP accomplishments grouped by NCSS objectives.

Informing Management (NCSS Obj. 1 – 3) • Habitat-linked salmon life cycle models • Salmon habitat capacity evaluations around passage barriers • MSE for several species, including sardines (Future Seas), sablefish, hake • EcoCast data tool for sustainable fisheries • Ship strikes on whales • California Risk Assessment and Mitigation Program (RAMP) • Central Valley Temperature Mapping and Prediction (CVTEMP) • Sablefish recruitment Model • CHaMP habitat monitoring • Whale Watch
Understanding Mechanisms and Projecting Future Conditions (NCSS Obj. 4 & 5) • Future Seas (downscaled future scenarios for CCLME biogeochemistry) • Climate and Communities Initiative • Forage species displacement due to thermal change • Bycatch mitigation and increased opportunity of target species • Location, Location, Location, case study • Ecosystem Shifts case study • Stream Temperature modeling • J-SCOPE seasonal forecasts • Salmon and marine fish climate vulnerability assessments • Potential species displacement and species invasions
Infrastructure and Tracking Change (NCSS Obj. 6 & 7) • CalCOFI quarterly and salmon surveys, stream temperature modeling, ocean entry modeling, Juvenile Salmon and Ocean Ecosystem Survey (JSOES) • Newport Line and associated NCC Surveys, ecosystem models • Coast Watch, CC MHW tracker, all surveys • Ecological models, SST • Ship positions, ecosystem models • West Coast regional Coast Watch, Coastal comparison index, HABS monitoring • UAV surveying, temperature monitoring • ERDDAP Webserver • RREAS

6.2 Activities and Progress

Build and Maintain Adequate Science Infrastructure (Objective 7)

The base of the pyramid is to build and maintain adequate science infrastructure. This is the core element of the Centers, collecting the scientific information needed to accomplish any mission goals. Science infrastructure includes the ships and the scientific cruises, fieldwork related to marine and anadromous species, the laboratory facilities necessary for processing samples, computer resources, and data management, and the scientific, technical, and administrative staff.

Surveys

Maintaining the ability to collect, process, and analyze data is a core requirement of any type of fisheries management. The extreme climate variability over the last few years, headlined by the 2014-2016 Marine Heat Wave (MHW), illustrates the need for regular monitoring of the environment and ecosystem to enable advances in scientific understanding and effective management responses.

Most of the West Coast Fisheries cruises were designed to obtain the data required for specific stock assessments. Thus, while ecosystem data are collected, ecosystem science and EBFM were not a primary objective in the original design of field campaigns, thus data from different cruises are not necessarily compatible with one another or easily placed in an ecosystem context. One WRAP goal that is still in formulation is a systematic review of West Coast cruises to find efficiencies and better integration across ecosystem components. One successful example of combining objectives was the 2018 joint Coastal Pelagic Species (CPS) and Marine Mammal survey of the entire U.S. West Coast.

The California Cooperative Fisheries Investigations (CalCOFI; https://calcofi.org) quarterly cruises, the Rockfish Recruitment and Ecosystem Assessment Survey (RREAS), the Juvenile Salmon and Ocean Ecosystem Survey (JSOES), the Newport hydrographic line (and associated Northern California Current survey), and the more recently established Trinidad line are examples in which ecosystem data considerations contribute significantly to survey design. CalCOFI was initiated in the late 1940s to understand the ecosystem factors involved in the collapse of the sardine fishery. RREAS cruises have provided foundational data for integrating physical and biological models to study ecosystem dynamics off California involving krill, sea birds, salmon, juvenile rockfish, and sea lions. JSOES was established in 1998 and represents a 20+ year time series of the pelagic ecosystem in the Northern California Current. Within this time series, both nekton and large zooplankton experienced large deviations from long-term means in response to the climatic and oceanographic events that produced the recent marine heat wave of 2014-2016. In addition, the survey established the appearance of novel organisms such as pyrosomes in the NCC in response to the marine heat wave (Morgan et al., 2019). The Newport and Trinidad lines monitor hydrographic and zooplankton parameters on a finer time scale, providing important lower trophic level information. Recent studies have shown the value of combining data across multiple surveys to evaluate climate-relevant questions, such as the impact of marine heatwaves on different life stages of key forage species (Muhling et al., 2020). The WRAP team continues to support these monitoring efforts.

Fresh water and nearshore monitoring

The NWFSC developed the Columbia Habitat Monitoring Program (CHaMP; https://www.champmonitoring.org) to generate standardized freshwater habitat status and trends data in at least one population within each steelhead and spring Chinook Major Population Group in the interior Columbia River Basin that had, or will have, juvenile and adult abundance and survival data collected through passive integrated transponder (PIT) tagging, smolt-trapping, visual observations, or other studies. All CHaMP metrics are then used to estimate habitat parameters throughout stream networks.

When coupled with fish sampling data collected by ISEMP and other salmonid management entities, CHaMP metrics were used to evaluate the effects of targeted restoration activities occurring as part of ongoing recovery efforts, and to support strategic project planning and implementation.

The NWFSC also developed the Salmon Habitat Status and Trends Monitoring[29] (SHSTM) program for four distinct salmon and steelhead spawning and rearing environments: large rivers, floodplains, estuaries, and the nearshore. We evaluated 115 potential metrics for monitoring large river, floodplain, estuary, and nearshore habitats, and used evaluation criteria to select 22 metrics that were both cost-effective and sensitive to change. Advantages of the new protocols are that they predict freshwater productivity of salmon, they can detect habitat change due to habitat restoration or natural channel movements, and they can identify estuary and nearshore restoration opportunities.

All of the SHSTM metrics can be expanded to monitor habitats in other river and nearshore systems in the Western Region. To measure the effects of climate change, floodplain habitat metrics have been adapted to assess how historical floodplain habitat losses have decreased their capacity to support salmon, and to identify potential floodplain restoration opportunities across the Columbia River basin. The SHSTM metrics can also be adapted to project potential effects of climate change on salmon habitat across the Western Region by connecting these metrics to Global Climate Models, the National Water Model (NOAA), the NorWeST stream temperature model (U.S. Forest Service), and Sea Level Rise projections.

Remotely-sensed data

SWFSC is a leader in the use of UAS instruments for fisheries management. Originally used in the Antarctic to count bird colonies, the usage has expanded to include marine mammal migration monitoring, Southern Resident killer whale (SRKW) monitoring, and marine turtle

[29] https://www.fisheries.noaa.gov/resource/map/salmon-habitat-status-and-trend-monitoring-program-data#:~:text=The%20SHSTMP%20is%20a%20long,using%20primarily%20remote%20sensing%20approaches

census counts. More recently, UAVs have been deployed in the Central Valley salmon monitoring to compliment salmon redd habitat surveys.

An important source of ecosystem data is from satellites, which provide global coverage of surface ocean properties at very high spatial and temporal resolution. NOAA NESDIS has supported the West Coast regional CoastWatch node (https://coastwatch.pfeg.noaa.gov) and now also supports the PolarWatch facility at the SWFSC. The integration of the satellite data with other environmental and ecosystem data has enabled development of multiple dynamic ocean management tools (see Adaptive Management Processes below).

The WRAP is fortunate to have an excellent webserver in ERDDAP[30]. The versatility of this web interface has been key to the development of indicators (see Track Change and Provide Early Warnings below). Continued development and more installations of the server have been critical to the development of condition tables like the Columbia River salmon stoplight table[31].

Collaborations and future planning

Two areas where the Centers do not have in-house expertise are nearshore monitoring (inside the three-mile limit) and development and implementation of ocean circulation models. Collaborations with other line offices and regional partners are critical for these functions. The three West Coast Regional Associations, NANOOS[33], CeNCOOS[33], and SCCOOS[32], have developed regional nearshore monitoring arrays and these data are accessible through their webservers (including the ERDDAP interface). The Integrated Ocean Observing System (IOOS) office has taken over the sponsorship of the Animal Telemetry Network. Our academic partners have taken the lead in operating numerical (ocean circulation) models and these are used in NMFS for multiple purposes. The NOAA National Ocean Survey is developing the West Coast Operational Forecast System (WCOFS), a Regional Modeling System data assimilative near-real time application. Some of the WRAP-related applications may transition to this platform when it reaches operational status.

Autonomous surveys

Unmanned data collection is becoming an essential component for evaluating ecosystem state and ecosystem-level processes. This type of technology is becoming increasingly desirable because it limits contact among the scientists, and can effectively sample ocean regions at relatively low cost. Manned surveys cannot obtain the spatial and temporal data needed to adequately sample the ecosystem variability or the seasonal progression (Schroeder et al., 2013; Wells et al., 2017; Friedman et al., 2018; Santora et al., 2020). Ship-based surveys, critical for collecting in-hand observations (e.g., biological samples), when coupled to

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30 ERDDAP website - https://coastwatch.pfeg.noaa.gov/erddap/index.html
31 NOAA Ocean Ecosystem Indicators website - https://www.fisheries.noaa.gov/west-coast/science-data/ocean-ecosystem-indicators-pacific-salmon-marine-survival-northern
32 NANOOS - http://nanoos.org/; CeNCOOS - https://www.cencoos.org/; SCCOOS - https://www.sccoos.org/

autonomous survey platforms that enable sampling across broader spatiotemporal aspects of the CCLME, can be used to inform the ecosystem state at a given time and advance our understanding of the processes leading to that state.

Two efforts currently exist along the CCLME using ocean gliders to add value to our ship-based survey efforts. The SWFSC is planning to deploy three Slocum gliders in the Southern CCLME to pair with the 2020 summer CalCOFI survey. These gliders are equipped with oceanographic sensors and multifrequency active scientific echosounders and optical cameras to characterize the forage assemblage. As well, during 2021-2023, the NWFSC and SWFSC will deploy gliders in the Central CCLME and the Columbia River Plume equipped with a suite of advanced sensors to capture oceanography (CTD), forage availability (echosounder), the occurrence of acoustically-tagged salmon (Vemco), and the presence of marine mammals (passive acoustics) to pair with the JSOES survey. These efforts will be evaluated relative to ship-based collections for validation but, importantly, will provide unprecedented spatiotemporal coverage of the ecosystem.

Track Change and Provide Early Warnings (Objective 6)

An evolving suite of indices are maintained on the California Current Integrated Ecosystem Assessment (CCIEA) website[33]. We evaluate the status of the CCLME by interpreting a variety of environmental, biological, economic, and social indicators, and present the status report annually to the PFMC. Standard presentation formats have been adopted and the website also allows the user to customize the plots. The user can view a single index or build a dashboard showing multiple indices together.

The assemblage of indices and partnering with federal, state, and academic entities has led to multi-investigator, transdisciplinary projects that aim to provide management advice (Table 6.2).

Table 6.2. List of West Coast transdisciplinary climate-related projects that use CCIEA indicators, ecosystem observations, and models.

Future Seas	A physics-to-fisheries management strategy evaluation for the California Current System
J-SCOPE seasonal forecasts	Forecasts of ocean conditions relevant to fisheries management, protected species, and ecosystem health
California Current Marine Heatwave Tracker[34]	A tool for tracking marine heatwaves

[33] CCIEA website - https://www.integratedecosystemassessment.noaa.gov/regions/california-current
[34] Marine Heatwave Tracker website - https://www.integratedecosystemassessment.noaa.gov/regions/california-current/cc-projects-blobtracker

Dynamic Ocean Management	A framework for optimizing ecological and economic sustainability
Ocean Acidification	Risk to food webs and fisheries
Multi-model Inference	Strengthening our understanding of food webs in the California Current
Coastal Communities	Fishery participation in a changing climate
West Coast Sanctuaries	Applying the IEA framework to support marine resource management
Coastal Renewable Energy Development	Capturing energy from the motion of the ocean in a crowded sea
Whale Entanglement	Monitoring the factors that bring migratory whales in contact with fixed gear fisheries

Several current projects aim to take a systematic approach to understanding climate impacts on the CCLME, from the large-scale climate drivers, to environmental and multi-trophic ecosystem response, to socioeconomic impacts. Here we list three of the projects:

Coupled changes in biomass and distribution drive trends in availability of fish stocks to U.S. west coast ports. This study examined trends in the distribution and biomass of five commercially-targeted groundfish species (dover sole, thornyheads, sablefish, lingcod, and petrale sole) on the U.S. west coast to determine how their availability to fishing ports changed over 40 years. It showed that: 1) the timing and magnitude of stock declines and recoveries are not experienced uniformly along the coast when they coincide with shifts in species distributions; 2) greater vessel mobility and larger areal extent of fish habitat along the continental shelf buffered northerly ports from latitudinal changes in stock availability; and 3) landings were not consistently related to stock availability, suggesting that social, economic, and regulatory factors likely constrain or facilitate the capacity for fishers to adapt to changes in fish availability.

As part of the Future Seas project (https://future-seas.com), a socio-ecological framework integrating a spatially explicit and environment-informed catch model with a utility model that quantifies fishing revenues and costs was developed to assess the economic impact of time-area closures (Smith et al., 2020). As a case study, the lost economic opportunity due to the LCA (Loggerhead Conservation Area) time-area closure was estimated. A clear signal in economic impact was associated with a shift from warm to cool conditions in the California Current following the 1998 El Niño (Smith et al., 2020).

The evolution of harvesting portfolios among Pacific Northwest fishermen over the last 35+ years with explicit attention to changes in the structure and function of the albacore troll and pole-and-line fishery was examined (Frawley et al., 2020). The analysis indicated that both climate and management actions shaped the West Coast fishing portfolios and that impacts varied by vessel type, with medium and small fishermen relying on a diverse portfolio and the ability to opportunistically catch albacore to sustain their livelihood (Frawley et al., 2020).

Understand Mechanisms of Change (Objective 5)

The WRAP has developed a set of case studies (Figure 6.1) to demonstrate and explore the complexity and interconnectedness of responses to climate change. Each case study tackled a particularly vexing challenge with climate change projections, where progress needs to be made separately, with the intention of bringing the case studies back together for a holistic perspective on whole-ecosystem responses to novel conditions. The salmon case study addresses issues with anadromous life histories, particularly the importance of changes in phenology and carry-over effects between environments. The ecosystem shifts case study addresses the challenge of predicting new ecosystem states that do not follow linearly from historical time series. The final case study addresses range shifts, which further alter the strengths of species interactions and interact with the other two case studies. These are being pursued through a series of workshops and cross-Center collaborations.

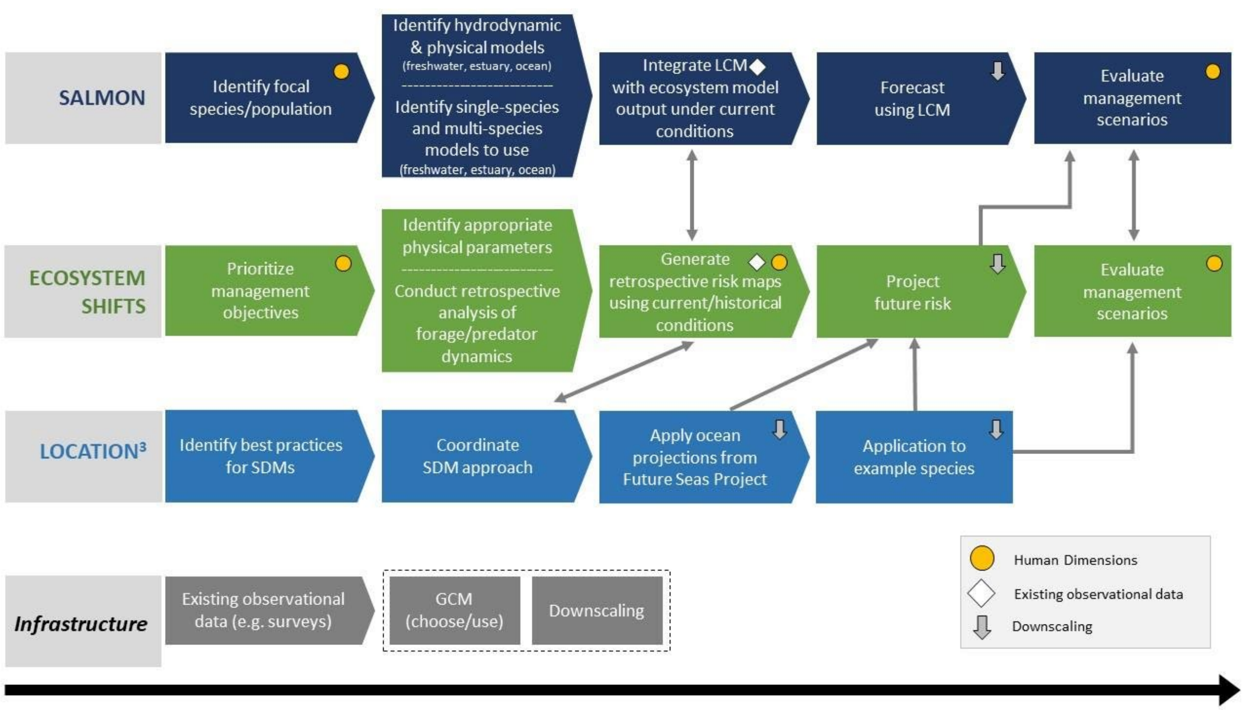

Figure 6.1. Description of the three WRAP case studies. All case studies rely on projections of future ocean conditions based on down-scaled output from an ensemble of GCMs. The arrows represent ways in which the case studies could interact.

Salmon Life Cycle Modeling for cumulative risk assessment in decision support
Anadromous species consistently top the list of species most vulnerable to climate change, based on northeast and west coast Climate Vulnerability Assessments (Hare et al., 2016, Crozier et al., 2019). Particular challenges with anadromous species involve integrating climate projections across environments (freshwater and marine) and accounting for changes in phenology and changes to the strengths of species interactions that will likely follow, including novel interactions due to range shifts.

Goals: The goals of this case study were to 1) develop methods of integrating climate projections across freshwater and marine environments, 2) incorporate projected change in climate drivers into all stages of the life cycle of study populations, 3) account for changes in phenology and body condition as carry-over effects, and 4) develop modeling tools for salmon responses to novel ocean conditions. Finally, 5) products will be used to inform management decisions.

Activities: We proposed four main activities to complete these goals. First, develop a life cycle model with climate projections in all life stages to begin to address goals 1-3. Second, improve understanding of how climate drivers affect growth and phenology in additional life stages through focused analyses. Third, parameterize and explore ecosystem models for the marine stage to better account for novel species interaction strengths and carryover effects. Fourth, integrate all of the previous pieces into a management strategy evaluation to compare management strategies under climate change projections.

Progress summary: Enormous progress has been made on these goals to date. Three publications were submitted to peer-reviewed journals demonstrating completion of activity 1 (Crozier et al., 2020, Chasco et al., 2021, Crozier et al., 2021). Importantly, the cumulative risk assessment incorporating climate change projections was used in the Columbia River System Biological Opinion (NMFS, 2020). Hollings Scholars and contractors worked on activity 2 over summer 2020, and work is on-going. Finally, we have initiated hiring a postdoctoral fellow to complete activities 3 and 4 in relation to marine survival.

Marine life stages proved to be the largest vulnerability quantitatively in Snake River spring/summer Chinook salmon (Crozier et al., 2021), but this response is likely to be common to many salmon species in the CCLME. Ecosystem models have not adequately addressed how bottom-up and top-down influences affect salmon vulnerability in a climate change context. Therefore, the most comprehensive part of this study for the next five years is to build a multi-model approach to ecosystem response to climate change in the northern CCLME. The first step of this process is to improve our modeling capability of the factors affecting salmon survival.

To reach this objective, we will kick off FY21 with a virtual workshop on March 8, 2021, analyzing alternative modelling frameworks for capturing uncertainty in trophic interactions. We will compare a wide range of approaches from qualitative network models, to fuzzy cognitive models, size-spectrum models, Bayesian belief networks, and multiple end-to-end model frameworks. Our goal is to actively select the best combination of approaches for a multi-model approach so that different models explicitly complement each other to inform important uncertainties. On-going work will improve models of these dynamics and explore potential management actions that could mitigate projected declines in this life stage. We will identify the data gaps that prevent fully quantifying potential benefits (and risks) of possible actions, and work with the survey analysis workgroup to develop a strategy to fill the most influential data gaps.

Ecosystem shifts

To examine ecosystem shifts we propose to 1) characterize environmental drivers of historical distributions of predators and forage, 2) retrospectively evaluate how variability in distributions of forage and predators related to productivity and condition of protected species and ESA-listed species of interest, 3) evaluate management strategies retrospectively for their capacity to have mitigated deleterious environmental, forage, and predator states, 4) model future climate change effects on predator-prey interactions and distributions, and 5) evaluate management strategies to mitigate potentially deleterious future environmental, forage, and predator states.

Shifting spatial distributions

The third case study is to investigate how climate change is expected to shift the distribution and migrations of the species that NOAA manages on the U.S. West Coast. Detecting and predicting these shifts are priorities under the NOAA Fisheries Climate Science Strategy. This case study is described in the next section in the “Location, Location, Location” workshop.

In all of the case studies, gaps have been identified where more human dimensions research is needed to prioritize the most pressing management objectives under changing climate conditions, identify climate impacts to coastal communities, and identify/evaluate human responses. Efforts to understand and explore the human responses to climate variation and change include further investigation into the socioeconomic consequences of the massive 2015 harmful algal bloom (HAB) that was caused (in part) by the 2014-2016 MHW. The 2015 HAB significantly disrupted the lucrative Dungeness crab fishery on the West Coast, generating an economic shock for fishery-dependent communities (Jardine et al., 2020; Fisher et al., in 2021). Stephanie Moore led work to identify the social, cultural, and economic impacts of the 2015 HAB on West Coast fishing communities (Ritzman et al., 2019; Jardine et al., 2020; Moore et al., 2020); identify effective coping and adaptive strategies; develop a framework for identifying fishing communities most vulnerable to HABs (Moore et al., 2020); document and evaluate management responses (Ekstrom et al., 2020); and conduct a resilience assessment of the West Coast Dungeness crab fishery system to future HABs.

Additional studies on climate-ecosystem linkages

In addition to the above case studies directly supported by the WRAP, the following research fulfills the WRAP mission of identifying mechanisms of climate impacts on living marine resources (LMRs). This foundational research addresses the goal of identifying future states of marine ecosystems, LMRs, and human communities. The following studies are setting the stage for informing both short and long-term stock projections through operational use of these climate drivers of recruitment and stock distribution in now-casts, short-term forecasts, as well as long-term Management Strategy Evaluations that allow for the consideration of future adverse or beneficial effects.

An NSF CNH-funded project, "The Dynamics of Adaptation to Climate-Driven Variability in California Current Fisheries And Fishing Communities", has explored how 1) environmental variability travels through, and is dampened or amplified by, linked social and ecological processes in fisheries systems on the U.S. West Coast; and 2) more integrated management of fisheries can be used to increase resilience and human benefits derived from West Coast commercial fisheries and other CNH systems. To date this project has demonstrated, among other things, that:

- Synchrony between species in the CCLME is driven by pelagic species, some of which had synchronous fluctuations with U.S. gasoline prices. This result suggests economic drivers on fishery behavior that influence fisheries synchrony. Other fisheries were synchronous with climate variability.
- West Coast fishing communities are experiencing climate-related ocean changes. Importantly, these changes are often compounded by (multiple and cumulative) stressors related to socioeconomic changes and management constraints. The impacts of climate and cumulative stressors to well-being is still being assessed from interview data.
- Fishermen utilize a variety of existing strategies to cope with changes, but there are fewer remaining novel types of actions available to fishermen to try. While many fishermen are diversified with permits for multiple fisheries, they are most often for fisheries occurring at different times of the year, leaving them little ability to move to another fishery when one is closed (Richerson and Holland, 2017; but see Fisher et al., 2021). In contrast, institutions and governments, while possessing a wider gamut of possible coping strategies, are not taking as varied an approach to meeting challenges.

Climate Vulnerability Assessments

Climate Vulnerability Assessments (CVAs) have been completed for West Coast salmon (Crozier et al., 2019), and are in final editing for 65 federally-managed fish species, including groundfish, coastal pelagic species, highly migratory species, elasmobranchs, and salmon[35]. A marine mammal CVA for the Pacific is currently underway. Social CVAs have paired the CVAs for specific fish species with the community vulnerability measures for those communities where those specific fisheries are most important. This identifies the communities where fishing-oriented climate shifts may be most acutely felt. The salmon CVA examined vulnerability at the Evolutionarily Significant Unit (ESU) level, which is the conservation unit under the Endangered Species Act. The WRAP and West Coast salmon CVA identified major gaps in our understanding and ability to project how salmon are likely to be impacted by climate change in freshwater and marine habitats.

[35] https://www.fisheries.noaa.gov/national/climate/climate-vulnerability-assessments

Hake and sablefish

Modeling efforts have focused on identifying climate drivers of both historical Pacific hake distribution (Malick et al,. 2020a) and using those analyses to produce short-term forecasts of Pacific hake distribution (Malick et al., 2020b) for stakeholder use. The historical analyses suggest that Pacific hake distribution is driven by interactions between age composition and environmental conditions and highlight the importance of accounting for varying environmental effects across multiple dimensions. Using 8-month lead-time predictions of temperature at 250 m depth from the J-SCOPE regional ocean model (Siedlecki et al., 2016), along with stationary habitat conditions (e.g., distance to shelf break), forecasts of Pacific hake (*Merluccius productus*) distribution in the northern CCE found strong agreement with historical observations. These Pacific hake forecasts demonstrate that seasonal lead-time ocean predictions have predictive skill for important ecological processes in the northern CCE and can be used to provide early detection of impending distribution shifts of ecologically and economically important marine species.

The ecosystem considerations analyses for the 2019 Sablefish stock assessment (Haltuch et al., 2019a) encompasses a broad range of studies that include 1) the CVA results, 2) mechanistic recruitment modeling using ROMs model outputs (Tolimieri et al., 2018), 3) a re-analysis of a long-standing sea level-recruitment relationship (Haltuch et al., 2019a), and 4) shifts in the center of the sablefish distribution in the California Current (Tolimieri et al., 2020).

Recent stage-specific and spatiotemporal modeling (Tolimieri et al., 2018) using Regional Ocean Modeling System (ROMS) output for the northern California Current area (40 to 48 °N) was able to predict 57% of the of the variation in age-0 recruitment not accounted for by the stock-recruitment relationship for years 1981 to 2010. A re-analysis of the relationship between sea level and recruitment conducted for the 2019 sablefish stock assessment that uses sea-level data from 1925 through 2018 found that variation around the stock-recruitment curve is negatively correlated with sea level north of Cape Mendocino. Lower sea level is typically correlated with stronger upwelling and southern alongshore surface flow (Connolly et al., 2014). However, lower sea level in the northern California Current is also related to a stronger alongshore sea-level/pressure gradient (higher in the south, lower in the north), which drives a stronger poleward deep current. This undercurrent is strongest between 100 m and 500 m, but poleward flows extend deeper.

Highly Migratory Species

Highly Migratory Species (HMS) such as tunas support valuable commercial and recreational fisheries along the U.S. West Coast, but their spawning grounds are located in warmer waters in the central and western North Pacific. Understanding potential climate change impacts on the future productivity of these species therefore requires consideration of processes occurring outside the CCLME. A study using outputs from the Pacific bluefin tuna stock assessment showed that recruitment was strongly predictable using SST on their nursery grounds (the region between Taiwan and the Sea of Japan) (Muhling et al., 2018). In particular, warmer SSTs around coastal Japan and in the East China Sea from summer to late fall were associated with above average recruitment. Although the underlying mechanisms are not yet clear, the strong predictive power of SST on Pacific bluefin recruitment could allow for more proactive management of this species under varying environmental conditions.

Food habits study
Knowledge of trophic interactions is fundamental to advising ecosystem-based fisheries management and integrated ecosystem assessments. Recent population crises in the CCLME have motivated interest in trophic ecology. These include a seabird unusual mortality (UME) event (2005), Central Valley fall-run Chinook salmon collapse (2007-2009), a California sea lion UME (2013), and increasing whale entanglements (2014-19). The Centers are developing a diet database for exploring the spatiotemporal variability of diet and trophic interactions of community members of the CCE: top predators (e.g., seabirds, mammals, highly migratory species), groundfishes (e.g., hake, rockfishes), coastal pelagics, and salmon. This study will make data from past and current empirical studies available to inform computational models that can be used to assess the effect of different environmental and management scenarios on CCLME communities. The results of the Food Habits study can be used in the ecosystem approach to fisheries management framework to inform single-species management by providing indicators of predation pressure, prey availability, and status of fish stocks.

Project Future Conditions (Objective 4)

Significant effort has gone into projecting future conditions. The 2014-2016 MHW provided a stress test on what conditions in a warmer future could look like. A number of efforts have built upon those conditions to explore possible future scenarios, both from an ecological and socioeconomic perspective.

During a March 23-25, 2020 WRAP workshop titled “Location, Location, Location”, 28 researchers assembled a suite of models to advance practices for modeling species distribution changes under climate change. Despite the COVID-19 crisis, we had excellent participation in a virtual environment, framed a core paper and some additional papers, brought in collaborators from around the U.S. and Canada, and made some advances in coding. A substantial part of the workshop focused on more fully testing the performance of different methods for species distribution models (SDMs) under projected future changes in ocean conditions. Mercedes Pozo Buil and Mike Jacox (SWFSC) from the Future Seas team made ROMS downscaled climate model output available to define future scenarios of ocean conditions. Stephanie Brodie, with assistance from James Smith, led much of the discussion around performance testing of the SDMs, drawing from Brodie et al. (2020). We expect SDMs such as boosted regression trees, GAMs, and VAST to each have different time scales (from 1-100 years) over which their performance degrades. During the workshop, sub-teams broke off to discuss code development for operating models, estimation models, and mechanistic or physiological models.

A major benefit of the “Location Location Location” meeting was linking up different national groups tackling SDMs (e.g., within the IEAs and NOAA DisMAP group), collaborating on code, and giving code and resources to scientists who are jump-starting their own involvement in SDMs. Next steps focus around development of the main paper (Stephanie Brodie as lead), applying downscaled climate model projections to ask how well SDMs can project species distribution shifts, and when/how these models fail. Additional papers focus on the use of fishery dependent data in SDMs (Melissa Karp as lead), and on SDMs utilizing CalCOFI surveys to consider long-term distributional shifts (Andrew Thompson as lead).

There are several efforts to develop and evaluate seasonal (1-12 month) forecasts of oceanographic and ecological conditions in the CCLME. Two projects that have been supported by NOAA's Climate Program Office and NMFS OST are developing downscaled forecasts, using ROMS, off the U.S. West Coast. One, J-SCOPE, is focused on the nearshore environment of the Pacific Northwest, while another, a SWFSC-UCSC partnership, is focused on the broader CCLME.

The J-SCOPE (http://www.nanoos.org/products/j-scope) model system provides 1-9 month forecasts of physical and biological conditions (currents, temperature, salinity, Chl-a, O_2, pH, and aragonite saturation state), off Washington and Oregon (Siedlecki et al., 2016). J-SCOPE is a collaboration between University of Connecticut, University of Washington-JISAO, NOAA, and other partners including state and tribal managers. J-SCOPE ocean forecasts have been translated into habitat and species distribution forecasts for sardine (Kaplan et al., 2016), Pacific hake (Malick et al., 2020b), and Dungeness crab larvae (Norton et al., 2019). These forecasts are also now routinely provided in the annual Ecosystem Status Report delivered to the Pacific Fishery Management Council. The J-SCOPE website and Siedlecki et al. (2016) detail the ROMS-based forecasting methodology, which provides skillful seasonal predictions of ocean conditions. This seasonal forecasting can help managers develop "climate ready" policies that complement longer-term climate scenarios, such as those from the Future Seas project described below.

As part of a MAPP-funded project, SWFSC/UCSC forecasts are based on a CCS ROMS grid that spans the U.S. west coast and extends ~1000 km offshore at a horizontal resolution of ~10 km (http://oceanmodeling.ucsc.edu). Reforecasts (i.e., retrospective forecasts used to evaluate their skill) have been produced for each year from 1982 to 2010 and they will be combined with ecological models (e.g., species distribution models for target and bycatch species) to assess the potential for proactive management actions in CCS fisheries. More generally, considerable attention has been paid to improving our understanding of predictability and forecasting methods for marine ecosystems (Jacox et al., 2020) and in understanding the predictability of extremes including marine heatwaves (Jacox et al., 2019).

The SWFSC has developed monthly average stream temperature predictions for all 1 km reaches in the western U.S. by expanding a pre-existing spatial stream network model (Isaak et al., 2017), currently only available for August, to all months of the year.

The NWFSC has developed approaches to constructing spatio-temporal estimates of stream temperature on a landscape-scale using remotely sensed Land Surface Temperature (LST) data from the NASA MODIS platform (McNyset et al., 2015). Summaries of site-specific hourly water temperature data from stream temperature loggers were used as response metrics and for model parameterization and validation. The statistical models include LST, Julian day, daily discharge at the mouth, and elevation as predictor variables and water temperature as the response variable. The predictive models are simple linear regressions by watershed and year for the heating and cooling phase of an annual seasonal cycle. This approach generates robust estimates of stream temperature through time for broad spatial regions for which there is only spatially and temporally patchy observational data. Predictions are typically made for weekly (8d) mean/min/max temperature at the spatial grain of NHD (National Hydrography Dataset) stream network reaches. Finer temporal resolution is possible, down to daily, but further increases in spatial and temporal resolution would require additional predictor covariates that generally are not available at the landscape (e.g., hydroregion) extent.

Stream temperature is also affected by local factors that may not be reflected in LST, so we incorporated riparian vegetation, discharge, and floodplain/complexity into the model. Manipulation of these factors allows for estimation of past and future stream temperatures as a result of climate change and restoration activities. Annual models have provided insight into the effects of extreme and common climate conditions on stream temperature. The modeling approach is robust to missing data, and can generate watershed-scale (USGS HUC4) predictions from a small number (~5) of stream temperature monitoring locations.

The NOAA/Climate Program Office (CPO)- and NMFS/ Office of Science and Technology (OST)-funded Future Seas project has over the past three years been developing frameworks for management strategy evaluation under climate change, with a focus on three west coast fisheries: swordfish, sardine, and albacore. The project is highly interdisciplinary, linking global climate to regional oceanography, ecology, and socioeconomics. A suite of climate projections for the CCS has been produced using the UCSC ROMS configuration forced by output from three global climate models that span a wide range of potential climate futures. The physical model is coupled to a biogeochemical model and is being used as input for a range of fisheries applications within and outside of the Future Seas project, including models of species distribution shifts, population changes, and trends in future socioeconomic metrics (e.g., landings, community fishing engagement).

As part of Future Seas, an individual-based model (IBM) of sardine and anchovy populations was forced by downscaled projections of ocean conditions and biogeochemistry to assess climate impacts on anchovy and sardine biomass and distribution. To better assess uncertainty in biological responses to climate change, projected changes in sardine dynamics have also been assessed with a spatial distribution model (SDM, Muhling et al., 2019) and a Model of Intermediate Complexity for Ecosystem Assessment (MICE). Outputs from the SDM model have been integrated into a socioeconomic analysis to assess the impacts of projected changes in sardine distribution on landings by port (Smith et al., 2021). Results indicate that warming of the California Current and subsequent distributional shifts in sardine habitat could result in considerable and regionally discrepant changes to port-level landings (Smith et al., 2021). A similar approach is being used to project changes in albacore landings, with output from an SDM and a population dynamics model being integrated into a statistical economic model of landings by port, which will enable assessment of socioeconomic impacts of albacore distribution and biomass changes under various management strategies. Community engagement indices based on PacFIN data for 1981-2016 have been developed for the albacore fishery, and are being developed for the sardine fishery. Work is ongoing to link these indices to the socioeconomic analyses above to assess the fishing community impacts of changes in landings by port driven by projected changes in albacore and sardine distribution.

Taking a longer view of regional ocean and ecosystem projection, the WRAP team is fully engaged in NOAA's cross line office Climate and Fisheries Initiative (described previously in Section 2.2 of the National chapter). As that initiative moves forward, it will both advance and benefit from WRAP activities.

Influence of changing sea surface temperatures on fall Chinook salmon distributions
To understand how a prominent anadromous species responds to ocean climate, Shelton et al. (2020) used spatio-temporal models to jointly estimate the ocean distribution of major fall-run Chinook salmon stocks from California to British Columbia over 40 years. Using hundreds of millions of tagged Chinook salmon, the authors show that individual stocks of Chinook salmon have fundamentally different average ocean distributions, distinct associations with sea surface temperature (SST), and contrasting distributional responses to historical ocean SST variation. Together these results suggest that species-level estimates of ocean distribution for Chinook salmon that ignore among-stock variation will likely be misleading. Future SST based on global climate projections for 2030–2090 suggest that average future SST will be comparable to strong events from recent decades. Application of future SST projections for six focal stocks of fisheries importance showed substantial predicted re-distribution of Chinook salmon in the ocean in response to SST change. In aggregate across stocks, there are predicted to be regions where abundances increase (British Columbia, central California) while others decrease (northern California, Washington); distributional changes do not follow a simple, poleward shift. Changes in distribution have implications for both major fisheries and marine mammal predators of Chinook salmon. This study focused on the consequences of spatial changes in ocean distribution, but our approach provides structure that can facilitate linkages between marine and freshwater components of anadromous species under climate change.

Adaptive Management Processes (Objective 3)

A variety of adaptive management decision-support tools are now being developed and used by NMFS on the West Coast. The CVTEMP decision-support project supports salmon spawning and incubation habitat management in the Sacramento River. Dynamic Ocean Management[36] is an approach for optimizing ecological and economic sustainability by incorporating spatiotemporal movements of both the target fishery species and bycatch and protected species to be avoided. Dynamic maps have been produced that allow fishers to optimize opportunity to harvest the target species while minimizing potential bycatch of protected or endangered species. Four examples of dynamic ocean management are EcoCast, WhaleWatch, RAMP, and loggerhead conservation.

[36] Dynamic Ocean Management website -
https://www.integratedecosystemassessment.noaa.gov/regions/california-current/dynamic-ocean-mgmt

EcoCast (https://coastwatch.pfeg.noaa.gov/ecocast) is designed for the California Drift Gillnet fishery to maximize catch of targeted species like swordfish while minimizing incidental bycatch of protected species such as leatherback sea turtles and sea lions, and non-target species such as blue sharks. Using remotely sensed oceanographic data combined with animal distribution data (surveys, fisheries catch, telemetry), EcoCast has created statistical habitat models that can be used to predict the ratio of bycatch to targeted catch in near real-time (Hazen et al., 2018).

Loggerhead turtles are rare-event species in fisheries records yet like leatherback turtles, Pacific loggerheads are endangered. There is a closure in the southern California Bight that is triggered by “El Niño-like conditions in southern California.” It has only been triggered a dozen times since inception, but with increasing frequency since late 2014. Opportunistic, shipboard, and plane-based sightings of loggerheads have been used to build a regional SST indicator termed TOTAL[37] that provides an indication of warm-water events that have been correlated with increased sightings, and thus provide an improved metric for considering fishery closures (Welch et al., 2019).

A similar tool, WhaleWatch[38], was developed to help reduce human impacts to whales by providing near real-time information on where they are likely to occur and may be most at risk from ship strikes (Hazen et al., 2017, Abrahms et al., 2019). There is increased effort to expand the models from EcoCast and WhaleWatch to additional implementations including whale and turtle entanglements, ocean noise, and long term marine spatial planning.

California’s Risk Assessment and Mitigation Program[39] (RAMP) is designed to reduce risk of whale entanglements in fixed gear fisheries. The indices that are available for this management tool are basin-scale climate/oceanographic indices, “compression” of coastal habitat, harmful algal blooms, the abundance of key forage species, whale abundance, and fishing activity (Santora et al., 2020). NWFSC and SWFSC staff are working closely with the RAMP to develop tools to inform the approach, including by developing a CCIEA website that provides a dashboard of relevant indices. The RAMP approach is currently adaptive in that there are regular meetings to assess the latest scientific data and make management decisions, but could be transformed to a dynamic approach with the establishment of thresholds and an automated decision tree.

We have also developed a suite of physical and biological models to predict and understand the response of salmon populations to water management and habitat restoration in California’s Central Valley. The Central Valley (CV) is home to numerous large water storage reservoirs, canals, engineered channels, flood bypasses, and water diversions that enable the rain and snow that falls in the winter in the north of the state to be distributed south and used year-round.

[37] TOTAL program website - https://coastwatch.pfeg.noaa.gov/loggerheads/
[38] Whale Watch website - https://www.fisheries.noaa.gov/west-coast/marine-mammal-protection/whalewatch
[39] California Risk Assessment and Mitigation Program website - https://www.opc.ca.gov/risk-assessment-and-mitigation-program-ramp/

This system and its operation has dramatic effects on hydrographs and water temperature patterns in river and stream reaches accessible to salmon, with largely detrimental effects on their populations. The question of how to balance the needs of humans and salmon for scarce water is a perennial one in California, and the design and operations of the water projects in the CV are under nearly constant scrutiny due to Biological Opinions and related lawsuits and co-management forums. We have developed a river temperature prediction system (CVTEMP; Danner et al., 2012; Pike et al., 2013), temperature-dependent egg mortality model (Martin et al., 2016), and a life cycle model that can link climate forecasts, management actions effects on hydrology, hydrodynamics, and water quality, and salmon population dynamics (WRLCM, Hendrix et al., 2014). This system has been used in several important Biological Opinions to date (e.g., Central Valley Biological Opinion[40]), with others planned in the near future.

Robust Management Strategies (Objective 2)

Scientists at both Centers continue to develop new tools for advancing ecosystem-based fisheries management, particularly with the inclusion of relevant ecosystem and climate information.

West Coast sablefish are economically valuable, with landings of 11.8 million pounds valued at over $31 million during 2016. A California Current sablefish MSE uses the sea level-recruitment relationship, projections of sea level from Global Climate Models (GCMs), and a suite of alternative harvest control rules to evaluate the robustness of alternative management approaches to projected sea level driven changes in recruitment through 2040 (Haltuch et al., 2019b). Recently, the Pacific Sablefish Transboundary Assessment Team (PSTAT), composed of scientists from Canada and the United States, is working on NE Pacific-wide data analyses in support of the development of a spatially stratified range-wide operating model that will serve as the basis for a NE Pacific Sablefish MSE.

Pacific hake is the most abundant groundfish in the California Current Large Marine Ecosystem (CCLME). Since 2011, it has been managed as a single stock through an international treaty between the U.S. and Canada. Growing recognition that environmentally-driven processes may act on hake of different ages has led to concerns that spatial population structure could affect harvest rates in both countries. A management strategy evaluation (MSE) is being conducted, with close collaboration of the hake management bodies, to 1) evaluate the performance of current hake management procedures under alternative hypotheses about current and future environmental conditions, 2) better understand the effects of hake distribution and movement on both countries' ability to catch fish, and 3) better understand how fishing in each country affects the availability of fish to the other country in future years. The MSE uses a closed-loop simulation framework, where data collection, assessment methodology, and harvest control rules are evaluated against known population dynamics specified in a spatial operating model.

[40] Central Valley Biological Opinion website - https://www.fisheries.noaa.gov/resource/document/biological-opinion-reinitiation-consultation-long-term-operation-central-valley

A recent review of environmentally informed forecasting and management strategy evaluations in fisheries applications (Haltuch et al., 2019c) reviews studies describing and hypothesizing the impacts of climate change and environmental processes on vital rates of fish stocks and, concomitant with that, the incorporation of these processes in fish stock assessments and forecasting models. This review suggests that the inclusion of environmental drivers into assessments and forecasting is most likely to be successful for species with short pre-recruit survival windows (e.g., squid, sardine) and for those that have bottlenecks in their life history during which the environment can exert a well-defined pressure (e.g., anadromous fishes, those reliant on nursery areas). Species with more complex early life histories and longer pre-recruit survival windows would benefit from future research that focuses on relevant species-specific spatio-temporal scales to improve mechanistic understanding of abiotic-biotic interactions. This review provides a set of additional research recommendations encompassing 1) life-history and mechanistic recruitment drivers, 2) modeling and recruitment forecasting methods, and 3) simulation studies and management implementation.

Management strategies to reconcile tradeoffs between fisheries sustainability and conservation in the context of rising whale entanglements

To address the rise in whale entanglements associated with the 2014-16 marine heat wave on the U.S. West Coast, especially in gear used by the Dungeness crab fishery, NWFSC and SWFSC staff are working closely with WCRO and staff at the California, Oregon, and Washington DFWs. This work has included the development of new models to describe the influence of changing ocean conditions on humpback whale distributions (Forney et al., in prep.) and the development of new data sets to reveal the spatiotemporal dynamics of fixed-gear fisheries (Feist et al., in review). A retrospective analysis of relative risk of entanglement in fishing gear for blue and humpback whales and relative revenue to the California dungeness crab fishery from 2009-19 under both status quo management and a broad set of hypothetical, alternative management scenarios was conducted (Samhouri et al., in prep.). The tradeoffs between whale risk and fishery revenue have grown starker in recent years with anticipated conservation benefits of management interventions increasing, but the expected costs to the fishery escalating even more. This tradeoff analysis framework provides a transparent approach for evaluating the effectiveness of management interventions designed to improve the lofty aims of fisheries sustainability while meeting mandates for the conservation of individual species. It also emphasizes that one-size-does-not-fit-all time periods, regions, species, or elements of a fishery, underscoring the importance of multicriteria decision approaches to navigating these uncharted waters.

Sardine MSE

A simulation analysis was used to examine how different methods for inclusion of environment-recruitment considerations in stock assessments influence the bias and precision of estimates of abundance and derived quantities that inform management decisions, using Pacific sardine as a case study (Crone et al., 2019). Results were used to identify good practices for including environmental considerations in stock assessments (Crone et al., 2019). Through Future Seas, work is underway to integrate the spatially explicit, climate informed sardine IBM in an MSE framework to assess the robustness of the current single area sardine stock assessment model in estimating management benchmarks given projected climate-driven changes in sardine biomass and distribution. The Future Seas sardine MSE framework is also being used to assess biological and socio-economic impacts of different management strategies, including harvest control rules with climate-informed reference points, to climate change uncertainty. This MSE work builds upon continued improvement in our understanding of environmental drivers of sardine recruitment derived from empirical studies (Zwolinski and Demer, 2019) and the mechanistic IBM and MICE models being developed as part of Future Seas (Section 4).

As part of Future Seas and leveraging the modeling capabilities developed in Smith et al. (2020), an MSE framework including spatially explicit swordfish catch models and leatherback bycatch models informed by ROMS, and a spatially explicit fisher behavior model, was used to compare effectiveness of closure scenarios for achieving management objectives under climate variability.

Climate-informed Reference Points (Objective 1)

The Future Seas and related projects are evaluating management strategies for albacore tuna, swordfish, and Pacific sardines under climate change. We developed an MSE framework to test performance of harvest control rules and reference points for North Pacific albacore in relation to a set of management objectives defined in collaboration with stakeholders (Tommasi and Teo, 2019, ISC 2019). Robustness of alternative limit and target reference points under a range of uncertainties, including interannual and cyclical variability in recruitment, and changes in mortality and growth, was tested (Tommasi et al. 2019, ISC, 2019). Results of a first set of simulations were shared with stakeholders, which requested the MSE framework be used to test additional harvest control rules and reference points (ISC, 2019). Those simulations are ongoing. An albacore spatial distribution model for the California current informed by ROMS output (Muhling et al., 2019) and socio-economic modeling capabilities developed via Future Seas are being coupled to the MSE framework to develop performance metrics relevant to domestic stakeholders (such as community engagement indices and landings by ports) and to assess robustness of management strategies to climate-driven changes in albacore availability.

Ecological thresholds in forecast performance for key United States West Coast Chinook salmon stocks

Preseason abundance forecasts drive management of U.S. West Coast salmon fisheries, yet little is known about how environmental variability influences forecast performance. Satterthwaite et al. (2019) explored how well environmental indices (at multiple locations and time lags) explained performance of forecasts based on different methods (i.e. sibling-based, production-based, environment-based, or recent averages), testing for nonlinear threshold dynamics. The specific focus of the study was on forecasts of Chinook salmon (*Oncorhynchus tshawytscha*) for 1) key California-Oregon ocean fishery stocks and 2) high priority prey stocks for endangered Southern Resident Killer Whales (*Orcinus orca*) in Puget Sound, Washington. For the California stocks examined, no index tested explained >50% of the variation in forecast performance, but spring Pacific Decadal Oscillation and winter North Pacific Index during the year of return explained >40% of the variation for the sibling-based Sacramento Fall Chinook forecast, with nonlinearity and apparent thresholds. This suggests that oceanic conditions experienced by adults (after younger siblings returned) have the most impact on sibling-based forecasts. For the Puget Sound stocks examined, multiple indices and lags produced nonlinear/threshold relationships explaining >50% of the variation in forecast performance. Environmental influences on preseason forecasts may create biases that render salmon fisheries management more or less conservative, and therefore could motivate the development of ecosystem-based risk assessments.

6.3 Synthesis across WRAP-relevant efforts for MSE and cumulative risk assessment

The success of WRAP, in large part, relies on the integration of products across projects. Namely, an ecosystem approach by its nature requires elucidation of processes accumulating across the ecosystem components. This in turn requires a transdisciplinary approach through integration of oceanographic data, biological survey data, and human dimensions. Specific examples of this approach are not common but a few can be highlighted. These examples are meant to demonstrate specific issues addressed by a synthetic approach but they provide a roadmap toward a more generalized approach for building EBM strategies.

Salmon example: A life-cycle modeling effort and resulting risk assessment were based on a decade-long study of the California Current ecosystem and the impacts it can have on survival in the freshwater and early out-migration periods of salmon (Friedman et al., 2019). Much of this enormous effort was initiated to elucidate the causes and consequences of the 2007-2009 collapse of the Central Valley Chinook salmon fishery and identify improved management strategies going forward. Individual research and modeling efforts determined a number of significant factors affecting salmon productivity/survival including experimentally-informed rearing temperature and numerical modeling efforts (Danner et al., 2012; Pike et al., 2013; Martin et al., 2016), freshwater predation of tagged fish during outmigration (Henderson et al., 2019; Michel et al., 2020), ocean productivity (e.g., sea surface temperature, upwelling; Schroeder et al., 2013), survey estimates of forage dynamics at sea (Wells et al., 2012; Friedman et al., 2018), agent-based models in the ocean (Fiechter et al., 2015; Henderson et al., 2019), food habits of predators, and survey estimates of predation on salmon (Wells et al., 2017). While each of these efforts was of value, a demonstration of the sensitivity of salmon to each must be taken in the context of their additive effects within and across life stages. Only then can a cumulative risk assessment and potential management scenario evaluation approach be taken to mitigate future events. For example, Friedman et al. (2019), Figure 6.2 incorporated these suites of data and study outcomes into a life-cycle model that capably captured variability in salmon recruitment success and provided a sensitivity analysis. Risk assessment, it was determined, should focus largely on freshwater temperature, out-migration flow, and marine predation as these were the dominant covariates of salmon recruitment. The model was also used to assess the potential of various management scenarios in freshwater that could potentially mitigate variability in mortality at later life stages.

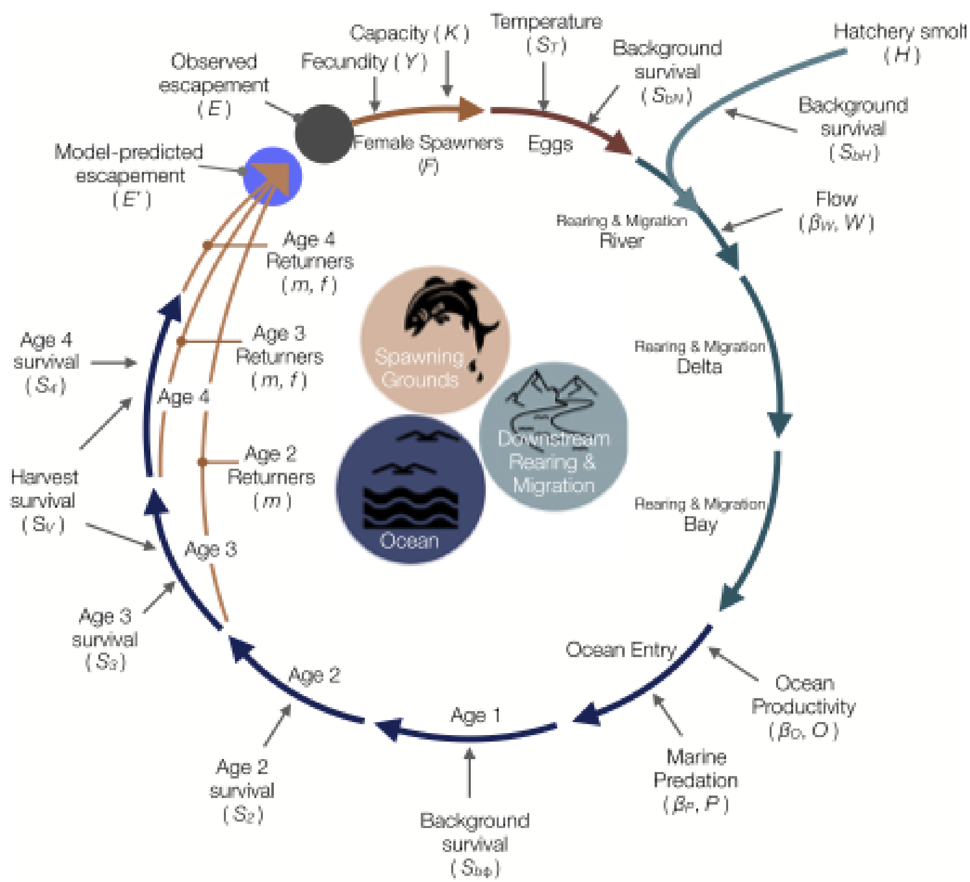

Figure 6.2. Friedman et al. (2019) provides an example of how integration of efforts across WRAP-relevant projects can be used to address ecosystem-level needs. Such a model has been capable of capturing salmon recruitment variability and identifying the factors to which salmon survival is most sensitive. Thus, this approach allows for quantitative cumulative risk assessment and management scenario evaluation.

Whale entanglement example: Within the central CCLME, ecosystem-level research successfully informs management to reduce the potential of whale entanglements (i.e., RAMP). Namely, an integration across existing research efforts was instigated by an anomalous increase in whale entanglements with fixed-gear fisheries during the 2014-2016 MHW. Santora et al. (2020) demonstrated that persistent ocean warming resulted in habitat compression, causing decline in cooler, upwelling habitat and altering the distribution and abundance of forage species and subsequently the shoreward distribution shift of humpback whales, leading to higher co-occurrence with Dungeness crab fishing gear and record numbers of entanglements (Figure 6.3). Note, each of these model inputs results from efforts outlined in this synthesis and their cumulative effect on ecosystem function was the result of integrating across observational and modeled-based oceanography (in situ, satellite, and ROMS, e.g., Schroeder et al. 2014), survey-based biological observations of forage and predators (RREAS), spatiotemporal dynamics of the fishery, and the interactions of human dimensions and ecosystem dynamics. Importantly, the work in Santora et al. (2020) was conducted in partnership with a diverse stakeholder group to ensure that ecosystem science helped guide considerations for developing recommendations to manage the crab fishery in order to mitigate the whale entanglement problem. In response, the California Department of Fish and Wildlife convened the California Dungeness Crab Fishing Gear Working Group, in partnership with California Ocean Protection Council and National Marine Fisheries Service, to apply an ecosystem perspective for assessing entanglement risk to wildlife and socio-economic impacts to the fishery. This working group uses RAMP to examine risk of entanglements throughout the fishing season and advises Dungeness crab fishery timing and extent in the context of ocean-climate and ecosystem conditions. More specifically, through synthesis of ecosystem science, Santora et al. (2020) provided the context for understanding and communicating risk attributes from an ecosystem perspective.

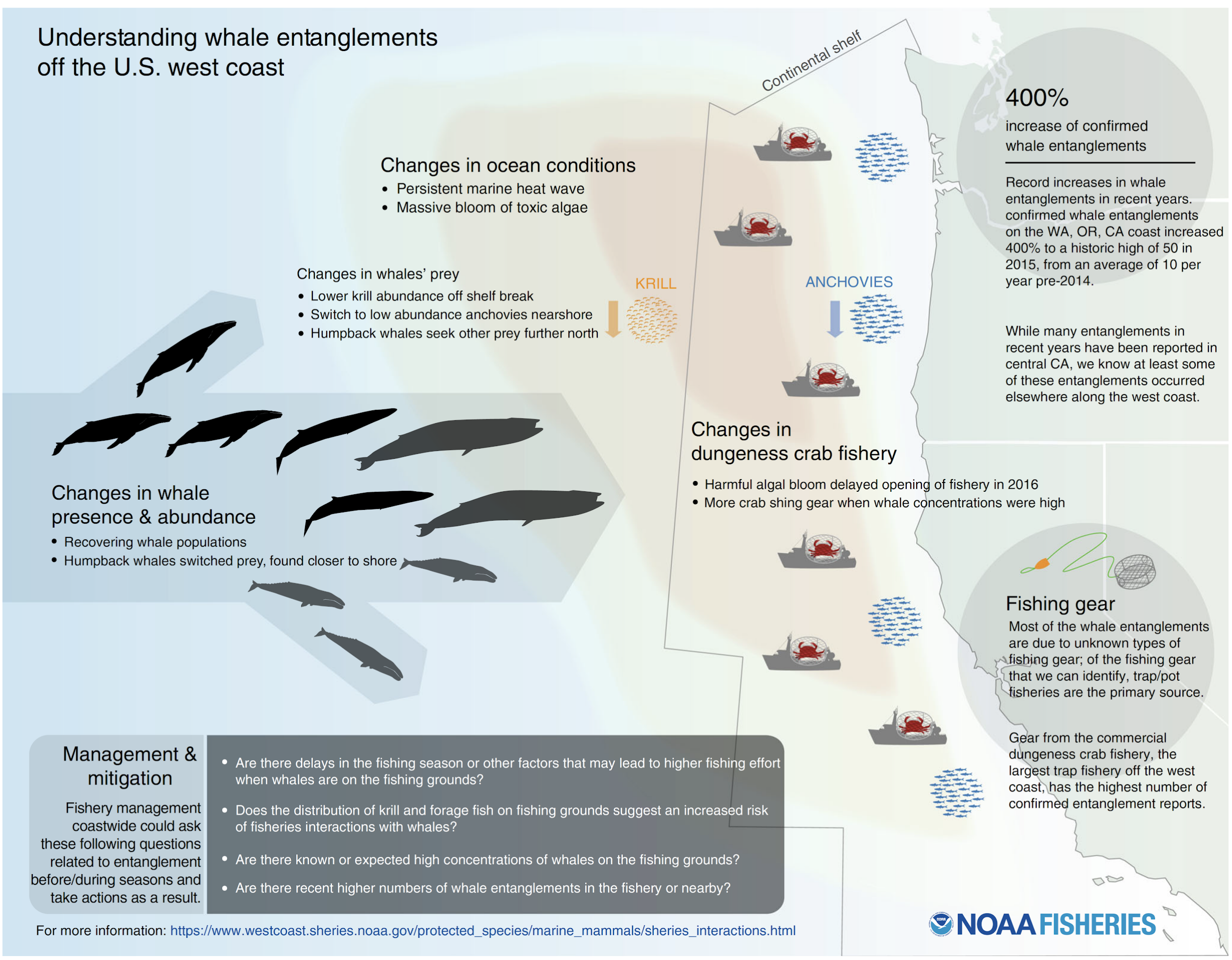

Figure 6.3. In diagnosing the processes underpinning the environmental role on forage and predator dynamics and how each interacts with the fisheries, Santora et al. (2020) synthesized the numerous efforts across WRAP-relevant projects. This provided the context for understanding and communicating risk attributes from an ecosystem perspective.

Integrating efforts to develop strategies to reduce likelihood of ecological surprises

Friedman et al. (2019) and Santora et al. (2020), among others, provide case studies for elucidating and mitigating dramatic, unexpected events. However, over the last 2 decades numerous ecosystem-level perturbations have occurred resulting from variability in predator behavior associated with environmentally-driven forage spatiotemporal variability (e.g., salmon collapse (Wells et al., 2017), sea lion unusual mortality events (Wells et al., 2013; McClatchie et al., 2016), seabird wrecks, and whale entanglements (Santora et al., 2020). It is important to develop tools for building strategies capable of avoiding these "ecological surprises" (Cury et al., 2008) in a future of increased environmental variability, increased forage variability, and increased predator consumption. WRAP developed a project titled "Ecological Shifts" for developing models to evaluate management strategies for reducing the probability and impacts of these ecological surprises in the future (Figure 6.4).

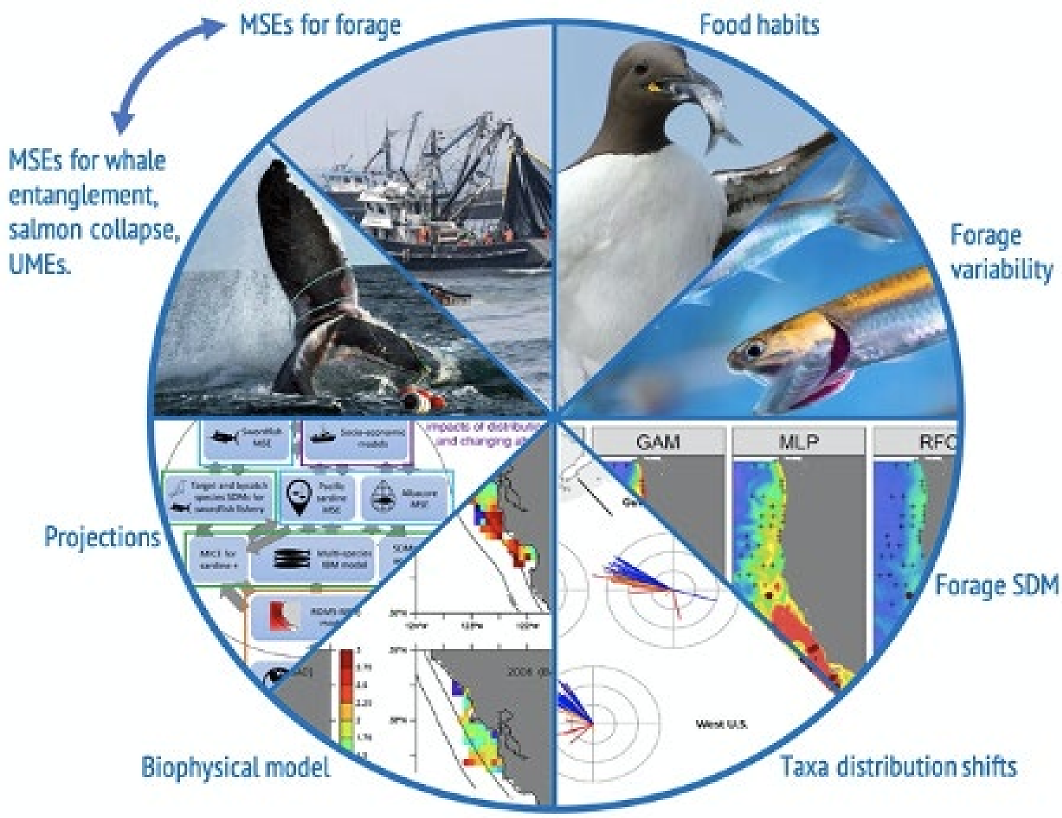

Figure 6.4. Illustration of the steps involved with implementing the NCSS pyramid for ecosystem-based fishery management. Beginning at the upper right with determining predator diet variability, the approach builds on progressively more integrated strategies of modeling forage variability and distribution andtaxa distribution shifts, develops projections, then movesto developing management strategy evaluations for individual species.

This is a synthetic approach building on progressively more integrated individual WRAP-relevant studies occurring in the SWFSC and NWFSC. Namely, this WRAP study focuses on identifying gaps hindering the integration of these projects and provides guidance/science for handshaking across divisions and centers to serve the needs of EBM and allow for a cost-effective, synthetic approach to EBM. These integrated products have been referenced in this report as individual studies or results from a suite of studies:

1. Food habits study to examine variability in predator diets (i.e., trophic structure) associated with environmental conditions
2. Spatiotemporal variability of forage assemblages (e.g., processes elucidated in monitoring efforts; Friedman et al., 2018)
3. Modeling forage species distributions (e.g., CalCOFI, RREAS)
4. Modeling taxa latitudinal shifts (i.e., Location, Location, Location; Pacific hake research)
5. Agent-based models of forage and predators (Fiechter et al., 2015, Henderson et al., 2019)
6. Developing models of future environmental state (e.g., Future Seas)
7. and 8. Management scenario evaluations to reduce the probability and impacts of novel surprises in the future (e.g., Friedman et al., 2019; Santora et al., 2020)

Management scenarios will be retrospectively evaluated using agent-based approaches and then selected scenarios will be run as future casts to evaluate their potential to mitigate the effects of climate change.

Table 6.3 lists WRAP-related programs and projects by NCSS objective.

Table 6.3. List of WRAP-related programs and projects. Note: URLs for the weblinks specified in the table are listed on preceding pages in the text or as footnotes.

Project(s)	**Web-Link**	**NCSS Objectives**
PFMC CCLME Fisheries Ecosystem Plan (2013)		2
Climate vulnerability assessment for West Coast Salmon and marine fish in the CCLME		4
Climate Ecosystem Science Committee projects: Food-habits, forage fish dynamics (distribution and productivity shifts)		4, 5
MSEs for sablefish, hake/whiting, swordfish, albacore, and sardine		2
Food Habits Database		
Nature Conservancy/PFMC Climate and Communities Initiative; Climate Scenario Planning for marine fisheries and salmon in the Puget Sound recovery domain		1-3
Assessments of economic and human community impacts		4-6

Project(s)	**Web-Link**	**NCSS Objectives**
CCIEA and CalCOFI state of the California Current Annual Ecosystem Reports	CCIEA and ESR	
Location-location-location, DisMAP		4-5-6
CBNMS condition report		
Dynamic Ocean Management Decision Support	RAMP ECOCAST WhaleWatch Loggerhead Turtles	3, 6
J-SCOPE – seasonal oceanographic forecasts for the northern CCLME	J-SCOPE	4, 5, 6
Ecosystem Surveys: RREAS, JSOES, Newport Line, Trinidad Head Line, NCC survey, CalCOFI, CPS		5, 6
Freshwater and nearshore habitat monitoring - Columbia Habitat Monitoring Program (CHaMP), Salmon Habitat Status and Trends Monitoring (SHSTM)		5, 6
UAS/UAV surveys: Ocean Gliders for temperature, salinity, current, and fluorescence transects Monitoring marine mammals, including SRKWs; monitoring turtles UAVs for CA Central Valley salmon redd mapping		5, 6
West Coast regional CoastWatch Node for accessing environmental and survey data	ERDDAP	6, 7
Partnerships with IOOS regional nodes	NANOOS, CeNCOOS, SCCOOS	6, 7
Partnership with NOAA/NOS West Coast Operational Forecast System (WCOFS)	WCOFS	4, 6, 7

Project(s)	Web-Link	NCSS Objectives
FUTURE SEAS		1-4
CCLME Marine Heatwave tracker		4, 6
MAPP forecasting		4, 6
WRAP Synthesis projects: salmon life cycle models, ecosystem shifts, and spatial distribution shifts		5
NSF CNH project: The Dynamics of adaptation to climate-driven variability in California Current Fisheries and Fishing Communities		2, 3, 5
Stream temperature modeling: RAFT (energy-budget model), landscape and remote-sensing spatial stream network empirical models		2-6
California salmon habitat management decision support	CVTEMP Winter-run Chinook salmon life-cycle model	2-5

6.4 A view of the next five years

A new project funded by the joint NOAA Climate and Fisheries Adaptation (CAFA) program ("*Impact of climate and ecosystem change on the California Current forage complex and the fishing communities and predators it sustains*")[41] will advance several of the WRAP strategic objectives. The project is based on the premise that for management to be most effective under future climate change, decision frameworks must capture interactions between environmental conditions, prey, and predators (including fishers). Through collaborations between the SWFSC, NWFSC, and other partners, a climate-informed decision-support tool will be developed to evaluate how harvest of forage species impacts ecosystem health, the trade-offs between increasing predator populations and target fisheries, and the performance of management strategies under climate and ecosystem uncertainty. Key elements of the workplan are to 1) project forage species habitat distributions in the CCLME under climate change, 2) assess the cumulative effects of multiple environmental and biotic drivers on the abundance and productivity of the forage complex, 3) produce projections of ecosystem state with associated uncertainty under status quo management, 4) assess impacts of climate change on coastal pelagic fishery participants, their portfolio, and the fishing communities they sustain, and 5)

[41] https://cpo.noaa.gov/Meet-the-Divisions/Climate-and-Societal-Interactions/The-Adaptation-Sciences-Program/Climate-Fisheries/Funded-Projects

compare performance of current single species catch advice versus alternative ecosystem-based catch rules in meeting management objectives, given the potential future impacts of climate change on the ecosystem and fishery participants. The project will run from September 2020 through September 2023.

One of the main knowledge gaps identified in climate change impact studies is the general lack of mechanistic understanding. Current work in the aquarium facility at the SWFSC is investigating the reduction of body size of marine fishes due to ocean warming, which has been observed across ecosystems and species. Of key interest is understanding the physiological mechanism that results in the reduction in body size, which has largely been untested. One hypothesized mechanism, the Gill-Oxygen Limitation Theory, has recently been adopted into models forecasting the impacts of climate change on fisheries, although it has drawn criticism as it is not based on valid physiological principles. In this collaborative project between NOAA, the University of California – Davis, and the University of Massachusetts – Amherst, these mechanisms will be explicitly tested in a model species that plays a key role in California food webs and fisheries, the Pacific sardine. The objectives of this project include: 1) quantifying the roles of oxygen limitation and gill surface area-body size relationships under variable temperatures, and 2) examining the relationships of energetic demands and life history trade-offs related to temperature and reduced body sizes. The results of this project are broadly applicable and of strong interest to managers and scientists within California and beyond, because alterations in body size are known to have significant implications on future fisheries yield projections, stock assessments, and ecosystem stability. Furthermore, a better understanding of the underlying physiological mechanism will provide the opportunity for accurate ecosystem and fisheries modeling.

6.5 Acknowledgements

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6.6 References

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7. Gulf of Mexico and Southeast U.S. Continental Shelf

7.1 Introduction

The Gulf of Mexico Regional Action Plan (GMRAP; Lovett et al., 2016) and Southeast United States Continental Shelf (SEUSCS; Gore et al., 2020) Regional Action Plan (S-RAP) were published in 2016 and 2020, respectively. These documents recognized that warming ocean temperatures, sea level rise, and ocean and coastal acidification would be key climate change drivers resulting in biological impacts in the Gulf of Mexico (Gulf) and SEUSCS. Understanding how major climate drivers such as these affect marine and coastal habitat distribution and quality, ecosystem productivity, and living marine resources is critical for natural resource management. Similarly, understanding and potentially forecasting climate driver impacts to threatened and endangered species and their key habitats is critical to protection of these species.

The GMRAP and S-RAP followed the approach presented in the NOAA Fisheries Climate Science Strategy (NCSS) (Link et al., 2015). The Regional Action Plans (RAPs) identified priority needs and specific actions to implement the NCSS in the Gulf and SEUSCS regions over a five year time period. Using a process that included input from stakeholders and the public, 62 actions in the GMRAP and 68 actions in the S-RAP were identified (130 actions in total) to help meet climate science needs.

Of the 62 actions in the GMRAP and 68 actions in the S-RAP, the highest priorities for climate science information and services included:

- Conduct climate vulnerability assessments for species in the Gulf and the SEUSCS, their habitats, and associated human communities. These analyses will help identify species especially vulnerable to climate change, identify research gaps, and set priorities for the region related to the management of species under the Magnuson-Stevens Fishery Conservation and Management Act, as well as the Endangered Species Act. (GMRAP Action 31, 32; S-RAP Actions 30, 31, 32)
- Use climate vulnerability assessments to identify and prioritize multidisciplinary data needs for climate science in the Gulf and SEUSCS. Data needs would include biological, climate, physical, chemical, socio-economic, and other necessary data, and identification of needs would be conducted in coordination with a broad range of federal, state, academic, and non-governmental organization partners. Gap analyses would be conducted to examine the adequacy of existing data and surveys to provide climate science information (GMRAP Actions 47, 49; S-RAP Actions 54, 56)
- Develop and regularly update Ecosystem Status Reports for the Gulf and SEUSCS. These reports will include information that can be used to track trends in indicators of

ecosystem health and would include a human dimensions component (GMRAP Action 36; S-RAP Action 39)
- Establish a formal Gulf and SEUSCS climate team that includes Southeast Fisheries Science Center (SEFSC), Atlantic Oceanographic and Meteorological Laboratory (AOML), Highly Migratory Species (HMS), and Southeast Regional Office (SERO) participants and others with regular meetings and communications. This team will share ideas, build capacity, strengthen collaboration with regional partners, and spearhead implementation of actions within the RAPs of the SEUSCS, Gulf, and the Caribbean (GMRAP Actions 53, 54; S-RAP Action 60)
- Develop and execute a monitoring plan that includes identifying new and maintaining existing critical baseline data for the Gulf and SEUSCS that supports climate science needs (GMRAP Actions 37, 38; S-RAP Actions 41, 56)
- Continue to build the capacity to consider climate science and environmental covariates in the stock assessment process, including using environmental covariates in stock assessments (GMRAP Actions 15, 49; S-RAP Action 15)
- Hire a management strategy evaluation (MSE) specialist to help identify harvest control rules likely to remain effective under future climate change scenarios (GMRAP Action 54; S-RAP Action 61)
- Collaborate with colleagues across NOAA and external partners to share ideas for developing climate-informed reference points through a workshop or meeting (GMRAP Actions 2, 3; S-RAP Action 1)

Since 2016, significant progress has been made to address the priority actions listed above in both the GMRAP and S-RAP. The following five-year summary organizes the efforts and accomplishments that have been made towards addressing actions in the RAPs as they relate to the NCSS objectives.

7.2 Activities and Progress

Build and Maintain Infrastructure (Objective 7)

Goal

Build and maintain the science infrastructure needed to fulfill NOAA Fisheries mandates under changing climate conditions.

Activity highlights

- Published the GMRAP and S-RAP as Technical Memoranda
- Developed the SEFSC and SERO climate change coordination team
- Planning a NMFS Atlantic Coast Science Coordination Workshop
- Developing regional trainings and workshops to advance partnerships
- Implemented a rotational assignment program to invest in staff professional development and strengthen expertise to meet climate science needs
- Held an SEFSC-AOML Climate Workshop

Progress summary
The S-RAP follows the same format as the GMRAP. Sixty-eight action items were identified, including eight priority actions.

A priority of the original GMRAP and S-RAP was to develop an SEFSC and SERO climate science team and to build collaboration between this team and other relevant offices including AOML. This team is being developed and currently a small group of SEFSC/SERO personnel meets regularly. A one-day workshop was held in 2018 between AOML and SEFSC to identify climate research priority areas. An in-person meeting was planned for summer 2020 across the Center and SERO to further establish connections, to review climate change activities, and to identify priority areas and future goals. This meeting was postponed due to COVID-19 and is now planned for 2021. Additionally, two SEFSC staff scientists were invited to attend (virtually) the GFDL-AOML coordination workshop in the summer of 2020.

A 4-day training course developed by the National Conservation Training Center (NCTC) to provide the skills and tools needed for climate adaptation application to on-the-ground conservation was scheduled for May 2020, but was also postponed indefinitely. The NCTC course will be taught in 2021 by NCTC staff alongside SERO and the Greater Atlantic Regional Fisheries Office (GARFO) instructors focusing on regional species case studies.

The NMFS Atlantic Coast Science Coordination Workshop was scheduled for 2020 to assess the degree of coordination of NOAA Fisheries science activities across the Northeast and Southeast U.S. Continental Shelf Large Marine Ecosystems, within the context of changing ecosystem conditions and shifting species distributions. This meeting was postponed to 2021.

A program to encourage rotational assignments between the SEFSC and SERO was developed, and although there have been no rotational assignments dedicated to climate change to date, the structure exists for future opportunities.

Tracking Change (Objective 6)

Goal
Track trends in ecosystems, LMRs, and LMR-dependent human communities and provide early warning of change.

Activity highlights
- Developed and updated Ecosystem Status Reports
- Developed Marine Mammal Assessment Program for protected species
- Collection of baseline data of fisheries-dependent, -independent, and habitat information

Progress summary
Ecosystem Status Reports (ESR) were considered high priority in the original GMRAP and S-RAP. An ESR was completed for the Gulf in 2013 and updated in 2017 (https://www.aoml.noaa.gov/ocd/ocdweb/ESR_GOMIEA/). The Gulf ESR analyzed a suite of 79 indicators and found that trends in some ecosystem pressures (sea surface temperature, sea level rise, ocean acidification) are now increasing at faster rates in some areas than in the prior

three decades. Further, areal coverage of natural habitats (e.g., seagrass, wetlands) are generally declining at the same time as the number of artificial habitats (e.g., oil platforms, artificial reefs) is increasing. An Ecosystem Status Report for the SEUSCS is near completion, and includes 182 time series across 48 distinct indicators and seven categories, ranging from climate drivers to fishery indicators and human dimensions. These reports are intended for use by Fishery Management Councils, local and regional management bodies, and other stakeholders, to complement species-level stock assessments and aid in risk analyses to guide fishery management decisions.

Marine Assessment Programs for Protected Species in the Gulf (GoMMAPPS; https://www.boem.gov/gommapps) and the SEUSCS (AMAPPS[42]) focused on incorporating environmental parameters into the development of spatially and temporally-explicit marine mammal density models, which are currently under development with products expected in early 2021. These products will be important for both NMFS regulatory needs (e.g., stock assessment reports, informing take authorizations, recovery planning for the endangered Gulf of Mexico Rice's whales - formerly Bryde's whales - and sperm whales) as well as the regulatory needs of other federal agencies such as Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE).

Collection of baseline data was considered a priority of the GMRAP and S-RAP. Multiple actions related to baseline data collection were undertaken, with some specifically to improve collection for protected species. Standard fisheries surveys continued, with some reductions due to the COVID outbreak. Focused protected species activities included collecting broad-scale information on the distribution and abundance of marine mammals, sea turtles, and sea birds in the southeast region (both Gulf and SEUSCS), and to integrate those data with historic survey data and *in situ* and remotely sensed oceanographic data to develop seasonally and spatially-explicit density estimates for priority species. Other action items conducted or underway include activities to map sea turtle nesting locations, as well as establishing a comprehensive plan for an in-water data collection program for sea turtles across the Gulf. This work has been funded by the Open Ocean Trustee Implementation Group of the Gulf restoration program. SEFSC staff are also involved in the decade-long mesopelagic fisheries project DEEPEND which is studying fishes and invertebrates beyond NMFS surveys in the open Gulf of Mexico.

Understanding Mechanisms (Objective 5)

Goal
Identify the mechanisms of climate effects on ecosystems, living marine resources, and resource-dependent human communities.

Activity highlights

- Developed methods for assessing the vulnerability of marine mammals to climate change
- Initiated fisheries climate vulnerability assessment for the Gulf (75 species)
- Initiated fisheries climate vulnerability assessment for the SEUSCS (71 species)

[42] AMAPPS website - https://www.fisheries.noaa.gov/new-england-mid-atlantic/population-assessments/atlantic-marine-assessment-program-protected

- Completed rapid climate vulnerability assessment for Gray's Reef National Marine Sanctuary (GRNMS) (11 fish, sea turtle, invertebrate species)
- Conducted research examining mangrove range expansion into salt marsh habitat
- Participated in a coordinated response with partners across the region (including the greater Caribbean) to stony coral tissue loss disease and non-native red lionfish
- Analyzed a 24 year time series of fish survey data from temperate reefs in the southeastern United States
- Used otolith biochronologies to explore snapper and mackerel growth linkages to the timing of the spring transition and the Atlantic Multidecadal Oscillation (AMO)

Progress summary
Climate vulnerability assessments of species, habitats, and associated resource-dependent human communities were top priorities for the GMRAP and S-RAP. Methodology was developed for assessing the vulnerability of marine mammals to climate change (Lettrich et al. 2019) and similar efforts are underway for sea turtles, with a global assessment of sea turtle climate vulnerability in progress. A rapid climate vulnerability assessment of marine resources in Gray's Reef National Marine Sanctuary, located off Savannah, GA, was also completed with participation from SEFSC and SERO scientists (Shein et al., 2019). In the Gulf, 75 species were assessed for climate vulnerability. Seventy-one species were assessed in the SEUSCS. Community vulnerability assessments conducted by social scientists follow fisheries vulnerability assessments in the Gulf and SEUSCS and have been initiated. Results of these assessments will be used to prioritize research for vulnerable species and inform and guide future management actions that may be affected by changing climate.

Research in the Gulf is examining climate-driven displacement and transition of ecologically important habitats. Estuarine nekton and benthic infauna in black mangrove and salt marsh habitats in coastal Louisiana have been sampled to assess potential changes in future fishery productivity (e.g., Gulf shrimp fishery). These data will be used to compare the distribution of nekton in these vulnerable habitats, develop habitat-specific food web models, and determine differences in fishery productivity of estuarine-dependent species. The study in the Gulf also has relevance for the SEUSCS, where black mangroves have been encroaching on salt marsh habitats as far north as St. Johns County, Florida (e.g., Guana Tolomato Matanzas National Estuarine Research Reserve). Note that a recent study (Johnston and Caretti, 2017) has shown that encroaching mangrove habitat provides inferior quality habitat in the presence of predation risk for *Callinectes spp*.

Stony coral tissue loss disease (SCTLD) has caused massive die-offs in the Florida Keys and Caribbean of numerous reef-building corals, affecting at least 24 species, yet little is known about the environmental and ecological conditions associated with these disease outbreaks (Muller et al., 2020). To address this multi-year mortality event, Southeast region scientists are participating in a coordinated response[43] to SCTLD that includes the establishment of a network of partners to address SCTLD impacting coral species in the region and greater Caribbean. Work groups have been created to address multiple aspects related to SCTLD, including rescue, research, restoration, and treatment.

[43] SCTLD response website - https://floridadep.gov/rcp/coral/content/stony-coral-tissue-loss-disease-response

Both the Gulf and SEUSCS are experiencing growing populations of invasive lionfish and the ecology of these species in these new habitats is not fully known. Eddy et al. (2019) studied two species of invasive lionfish (*Pterois volitans* and *P. miles*) in Bermuda using annual otolith growth rings and histological staging of ovaries. They found that lionfish in Bermuda grew faster and reached larger sizes than in their native habitats, but they reached maturity later and had a shorter spawning season. The authors argued that this was due to the cool winter temperatures and may mitigate or delay the impacts of lionfish in this newly invaded area.

Research on *Pterois volitans* on shallow reefs in the Caribbean and Bahamas reported that lionfish were found down to 91 m and could impact mesophotic reef communities (30-150 m; Lesser and Slattery,2011). These researchers found that lionfish reduced the diversity of several important guilds of fishes, including herbivores. The loss of herbivores in the system resulted in a shift to an algal-dominated community (>50% benthic cover) to a depth of 61 m. There was also a decline in both sponges and corals at mesophotic depths. These areas are thought to act as refugia, or a source of recruits, for shallower areas and some have said this could offer resilience to climate change (Holstein et al., 2015, but see Smith et al., 2016) for key coral reef taxa. These system-level changes have potentially eroded the resilience of these communities, thus impairing their ability to recover or contribute to the recovery of their shallow water counterparts.

Disentangling the effects of climate from commercial and recreational fishing in the analyses of survey data is part of building a mechanistic understanding of the impacts of climate change on living marine resources. In an analysis of 24 years of temperate-reef survey (chevron trap) data on the SEUSCS, Geraldi et al. (2019) found that climate (AMO and North Atlantic Oscillation [NAO]) and local temperature (bottom temperature and winter SST) effects accounted for most of the variation in fish community structure. Recreational fishing explained slightly more variation compared to commercial fishing in the temperate reef fish community over a multi-decadal scale. Further analyses indicated that bigger and longer-lived fishes were positively correlated with depth and winter temperature. The findings suggest that lesser-studied anthropogenic impacts, such as recreational fishing, may influence communities throughout large ecosystems as much as other better-studied impacts such as climate change and commercial fishing. In addition, climate indices should be considered when assessing changes, natural or anthropogenic, in fish communities. This effort addresses the following RAP actions: S-RAP Obj. 1, No. 2; S-RAP Obj. 1, No. 3; S-RAP Obj. 3, No 15.

Using otolith biochronologies for red snapper, gray snapper, black drum, and king mackerel in the Gulf, Dzaugis et al. (2017) examined the response of otolith spacing to the meteorological spring transition and to the AMO. They found that otolith spacing increased (decreased) when the spring transition was early (late) in red snapper, gray snapper, and black drum. King mackerel did not show the same pattern, but instead was negatively correlated with the longer term AMO signal. Dzaugis et al. (2017) argued that these differing responses were likely due to the movement patterns of the species. Snappers and black drum do not undertake the large basin-scale migrations characteristic of king mackerel. This study provided a linkage between two environmental processes (i.e., spring transition and AMO) and the growth rates of four fish species.

Projecting Future Conditions (Objective 4)

Goal
Identify future states of marine, coastal, and freshwater ecosystems, living marine resources, and resource dependent human communities in a changing climate.

Activity highlights

- Integrating broad-scale marine mammal distribution and abundance data into spatially-explicit density estimates as a function of remotely sensed oceanographic data to predict climate impacts
- Downscaled climate models for multiple regional-scale applications (e.g., assessing the vulnerability of species and their habitats to coastal flooding/droughts, biogeochemical changes, increased storm severity, and Gulf Stream oceanographic changes
- Used an ocean biogeochemical model and observations to link El Niño - Southern Oscillation (ENSO) to productivity on the northern Gulf of Mexico shelf
- Developed multiple social indicators to assess human risks from climate change (e.g., storm surge, sea level rise)

Progress summary
Multiple efforts are underway in collaboration with NOAA partners to retrospectively assess observed sea surface temperatures for the SEUSCS and Gulf and project future conditions. Historical records have been compiled and analyzed for the SEUSCS and the SEFSC is working to extend these analyses to the Gulf. These analyses will help validate downscaled climate models and improve forecasts.

A push to advance modelling efforts and techniques creates the need to develop a standard modeling toolbox and best practices for modeling under uncertainty. The ability to couple models across types and to link future ocean states and their living marine resources is a growing imperative. In 2018 a scoping workshop with scientists, managers, and other stakeholders was held to identify and prioritize challenges in the Gulf that could be addressed using ecosystem models, and how best to incorporate those models into the existing fisheries assessment and management framework. The need to integrate ecosystem processes into stock assessments was identified as a priority. The effort resulted in a peer-reviewed publication (Chagaris et al., 2019) intended to guide future ecosystem modelling efforts and advance ecosystem-based fisheries management in the region.

The SEFSC and AOML are collaborating on a project to downscale Coupled Model Intercomparison Project (Fifth phase, CMIP5) model projections to investigate potential shifts in ocean biogeochemical cycles. Additionally, scientists are using a high-resolution regional ocean-biogeochemical model (MOM-TOPAZ) to explore the potential linkages between large-scale climate and ocean variability and economically important species. Dynamic downscaling simulations of the CMIP6 (Sixth phase) models, which employ scenarios rooted in socioeconomic trajectories to characterize reasonable future scenarios, are currently being performed. Ultimately, this work will produce a downscaled biogeochemical model for use in fisheries studies as well as insight into physical forcing of fish species range shifts and/or productivity declines.

Existing downscaled models were used to assess species-specific climate vulnerability for nine key species found within the Gray's Reef National Marine Sanctuary (GRNMS). In 2017, GRNMS convened an expert workshop (Shein et al., 2019). Using a modified version of the Commission for Environmental Cooperation's North American Marine Protected Area Rapid Vulnerability Assessment tool, species experts transformed their knowledge into a vulnerability score for each species. Once climate vulnerabilities were established, participants discussed possible adaptation strategies which, if implemented, might reduce species vulnerability. These efforts illuminated top climate concerns for the nine species and also identified several non-climate stressors such as the invasion by lionfish, a species that may be less vulnerable to climate stressors than the native fish species assessed.

The Integrated Ecosystem Assessment program[44] funded a joint AOML-SEFSC project to use data-driven Bayesian network analyses to explore the potential impacts of climate change on commercially important species in the Gulf, resulting in a peer-reviewed publication (Trifonova et al., 2019). This analysis highlighted the strength and sensitivities of linkages between ecosystem components to climate perturbations, further elucidating the need to include climate variables in systems modelling and species assessments.

Protected species were the subject of climate related research focused on modelling future conditions. Impacts to sturgeon (shortnose and Atlantic) distributions were assessed under different climate scenarios and incorporated into a biological opinion for a South Carolina river facing drought-related water distribution impacts. A partnership between the Bureau of Ocean Energy Management (BOEM), the United States Fish and Wildlife Service (USFWS), the U.S. Navy (USN), Northeast Fisheries Science Center (NEFSC), and the SEFSC is currently collecting broad-scale information on the distribution and abundance of marine mammals, sea turtles, and sea birds in the SEUSCS. These data will be integrated with historic survey, *in situ,* and remotely sensed oceanographic data to develop seasonally- and spatially-explicit density estimates for priority species. The resulting models will enhance our understanding of how environmental parameters such as temperature, salinity, Gulf Stream, and eddy locations influence protected species distribution. A similar program is operating in the Gulf.

Gomez et al. (2019) used a regional ocean-biogeochemical model augmented by satellite and *in situ* observations to show that the ENSO is a main driver of the interannual variability in salinity and plankton biomass during winter and spring in the northern Gulf. They argue that ENSO, by modulating river discharges, winds, phytoplankton, and zooplankton production, could impact important species such as Gulf menhaden and red snapper. Interestingly, Leaf (2017) also found that winter ENSO is a leading indicator of oil content, an index of condition, for Gulf menhaden.

Finally, fishing communities were a focus of modelling efforts through the development of social indicators. Social indicators are numerical measures that describe and evaluate the social, economic, and psychological well-being of individuals or communities. They were developed to characterize community well-being for coastal communities engaged in fishing activities. A Storm Surge indicator was developed for the SEUSCS and Gulf coasts of the United States and represents a community's risk for storm surge based upon the amount of area that would be

[44] https://www.integratedecosystemassessment.noaa.gov

flooded by levels of storm surge from level 1 to 5. A separate climate change vulnerability indicator is currently in development and should be available midyear 2021.

Informing Management (Objectives 1 - 3)

Goals
Identify appropriate, climate-informed reference points for managing LMRs; identify robust strategies for managing LMRs under changing climate conditions; design adaptive decision making processes that can incorporate and respond to changing climate conditions.

Activity highlights

- Incorporated an index of the Atlantic Multidecadal Oscillation (AMO) into stock assessments for bluefin tuna and swordfish
- Incorporated an index of red tide severity into assessments for red and gag grouper
- Used connectivity modeling to help estimate recruitment deviations in red snapper, red grouper, and gag grouper
- Included climate and environmental covariates in determining the cause of marine mammal Unusual Mortality Events (UMEs)
- Hired an MSE specialist for the SEFSC

Progress summary
Schirripa et al. (2017) identified a relationship between the AMO and fleet-specific catch per unit effort (CPUE) in North Atlantic swordfish (*Xiphias gladius*). When the AMO was in a warm phase, the CPUEs in the western (eastern) areas of the stock's distribution were higher (lower) than predicted by the assessment model fit. Using the physiological temperature preference for swordfish, an environmental index of SST anomalies representing this relationship to the AMO was used to help parameterize catchability in the stock assessment model. This effort resulted in a better fit to the catch rate data and, by providing area-specific catch rates, afforded the ability to detect basin-wide responses to shifting oceanographic processes. This work is now routinely done for both swordfish and Western Atlantic bluefin tuna (*Thunnus thynnus*) for the International Commission for the Conservation of Atlantic Tunas (ICCAT). These are critical steps in providing robust management advice in a changing climate. This work addresses several RAP actions: S-RAP objectives 1 (no. 2, 3) and 3 (no. 15); GMRAP objectives 1 (no. 1,2), 2 (no. 8) and 3 (no. 15).

In 2005, an extensive red tide on the West Florida Shelf resulted in a significant fish kill that was recorded in NOAA ship Oregon II's log from the NMFS bottom longline survey. During a 2009 update assessment for red grouper (*Epinephelus morio*), it was found that spawning stock biomass levels had decreased since 2005. This decline was coincident with the 2005 red tide mortality event. In stock assessments since the update (and inclusive of the update), red tide events (e.g., 2005, 2014, 2015, 2018) were treated in the assessment model as a pseudo-fleet creating dead discards. The selectivity pattern assumed that ages-0 and older were 100% selected for by the red tide. The severity of the red tide events was estimated by the assessment model rather than imposed as an input. This approach thereby allowed the incorporation of this major, potentially climate-driven, environmental process into the stock assessment process. These assessments also used oral histories (Karnauskas et al., 2019) of fishers to assess the impacts of red tide events across the Gulf, and this approach has been extended to gag grouper (see Walter et al., 2013, 2015; Sagarese et al., 2014, 2018; SEDAR 61, 2019, for more information). A publication is in preparation by S. Sagarese (SEFSC) covering this red tide work called "Enhancing single-species stock assessments with diverse ecosystem perspectives: a case study for Gulf of Mexico Red Grouper *(Epinephelus morio)* and red tides." Overall, this work addresses the following RAP actions: GMRAP objectives 1 (no. 1, 2) and 3 (no. 14, 15).

Grüss et al. (2014) used output from the oceanographic circulation model HYCOM and the Connectivity Modeling System to simulate larval transport of Red Grouper across the West Florida Shelf. This modeling system produced an index of recruitment deviations attributable to spawning-season oceanographic differences between 2003 and 2013 that could be incorporated into the stock assessment model Stock Synthesis III. Perhaps more importantly, this effort demonstrated a capability in larval transport modeling that could be applied to the next generation of down-scaled climate models. Changes in recruitment success due to shifts in circulation patterns could be explored with the approach used in the red grouper work. A similar effort was used previously to examine gag grouper (*Mycteroperca microlepis*) transport processes (Karnauskas et al., 2013). Sagarese et al. (2015) incorporated both larval transport indices and red tide indices in a Stock Synthesis model for red grouper. The incorporation of larval transport interannual variation accounted for roughly 33% and 58% of the variation in the estimated stock-recruitment deviations for red snapper and gag grouper, respectively (Karnauskas et al., 2013; Karnauskas et al., 2017). These efforts address the following RAP actions: S-RAP actions in objective 1 (no. 2, 3) and 3 (no. 15) and GMRAP actions under objective 1 (no. 1) and 3 (no. 15).

Investigations of marine mammal UMEs now include the potential effects of climate and/or environmental parameters. Recently, Gulf UME investigations have included increased rainfall and freshwater inputs as a causal factor for the 2019 Northern Gulf dolphin UME and the role of red tide in the 2018 Southwest Florida UME. This addresses RAP actions under GMRAP objective 4 (no. 25).

Additionally, an MSE specialist was hired at the SEFSC to address climate change considerations as well as other MSE needs. This scientist is located at the Beaufort Laboratory.

7.3 Conclusions

Overall Progress and Accomplishments

Significant progress was made addressing RAP action items across a diverse range of climate-related activities in the Southeast region (Table 7.1). In the context of this Progress Report, it is important to recognize that RAP development teams were given instructions to consider cases of level funding as well as increased funding when formulating RAP activities. These instructions, together with input from colleagues, stakeholders, and the public, led to the development of 62 actions for the GMRAP and 68 actions for the S-RAP (a total of 130 actions for the Southeast region). The highest priority actions in the GMRAP included 12 items, the S-RAP identified 11 high-priority actions (a total of 23 actions). Accordingly, progress associated with this synthesis of RAP activities is measured by the degree to which high-priority actions were completed or addressed. There are differences in the percentage of completed priority actions between the Gulf and the SEUSCS (Fig 7.1) and this reflects the fact that formal development of the GMRAP preceded that of the S-RAP. Activities in both the GMRAP and the S-RAP addressed all seven NCSS objectives.

Table 7.1. A selection of Southeast activities addressing goals of the seven NCSS objectives.

Informing Management (NCSS Obj. 1 – 3) • Climate and environmental information has been successfully incorporated into multiple assessments (e.g., AMO - bluefin tuna and swordfish; red tide - red and gag groupers; oceanographic circulation - larval recruitment of groupers and snappers; freshwater discharge and red tide - marine mammal UMEs) • A management strategy evaluation specialist was hired whose duties will include using MSE to identify harvest control rules that remain effective under anticipated climate changes
Understanding Mechanisms and Projecting Future Conditions (NCSS Obj. 4 & 5) • Climate Vulnerability Assessments underway/completed in Gulf and SEUSCS for fisheries, marine mammals, and the GRNMS • Marine Assessment Programs for Protected Species in both the Gulf (GoMMAPPS) and the SEUSCS (AMAPPS). These efforts are federal partnerships between BOEM, USFWS, USN, NEFSC, and SEFSC to collect broad-scale information on the distribution and abundance of marine mammals, sea turtles, and sea birds in the Gulf and SEUSCS. The plan is to integrate these data with historic survey data and *in situ* remotely sensed oceanographic data to develop seasonally and spatially-explicit density estimates for priority species. • Social science indicators were developed to characterize the vulnerability and resilience of coastal fishing communities to climate change impacts such as sea level rise and storm surge, with additional indicators under development. • Southeast region scientists are participating in a coordinated response to stony coral tissue loss disease (SCTLD) that includes the establishment of a network of partners to address SCTLD impacting coral species in the region and greater Caribbean.
Infrastructure and Tracking Change (NCSS Obj. 6 & 7) • Ecosystem Status Reports: updated for the Gulf and nearing completion for the SEUSCS • Coordination of and participation in workshops for advancing the use of climate science in NMFS activities (e.g., Atlantic Coast Coordination, Gulf Ecosystem Modeling, SEFSC-AOML Climate RAP-support Workshop, NMFS-OAR Climate-Fisheries Initiative Workshop, GFDL-AOML Workshop, co-chaired Session 8 at the 4th International Climate Symposium.) • Established a comprehensive plan for an in-water data collection program for sea turtles across the Gulf. The plan has been funded but is not yet in operational the field • A program to encourage rotational assignments between the SEFSC and SERO was developed, and although there have been no rotational assignments dedicated to climate change to date, the structure exists for future opportunities.

Gulf of Mexico

Of the 62 actions in the GMRAP, 12 were identified as the highest priorities to be addressed or completed by 2020. Figure 7.1 shows that five of those 12 priority actions are complete (Actions 31, 32, 36, 47, and 54); three were begun and are considered ongoing (Actions 15, 2, and 3); three are in progress (Actions 49, 38, 53); and one is planned to occur (Action 37).

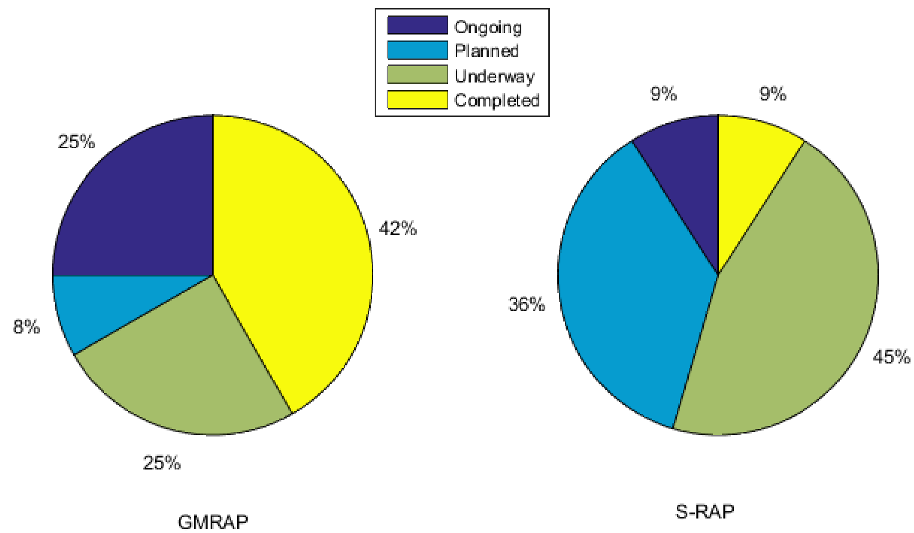

Figure 7.1. GMRAP and S-RAP progress on priority actions since 2015.

South Atlantic

Eleven of the 68 actions in the S-RAP were identified as priorities to be addressed or completed by 2020. Figure 7.1 shows that one of the priority actions is complete (Action 61); one is considered ongoing (Action 49); five are underway (Actions 1, 15, 31, 39, and 60); and four are planned to occur (Actions 32, 47, 56, and 41).

Aside from the CVAs and standing up climate working groups, much of what was accomplished was not specifically targeted to address RAP actions. Rather, it was work that was undertaken largely for other purposes and identified as climate-related when appropriate. This approach was specified in the RAPs themselves because it was known *a priori* that there would be personnel and funding limitations. Moving forward (i.e., RAP 2.0), the RAP team believes that it would be better to have more work specifically dedicated to completing RAP objectives. Additionally, in contrast to the large number of potential actions presented in the original RAPs (130 action items), fewer, more strategic, and actionable activities would be a better path forward. Of course, climate science touches nearly all aspects of work in the Southeast region. While not specifically responding to future targeted RAP priorities, a number of different activities will continue to take place that will contribute to RAP efforts along with targeted priorities.

Activities outlined in this synthesis were supported by a variety of sources including NOAA RESTORE, NOS (in the form of salary support), Office of Science and Technology (EBFM), the OAR Climate Program Office (Modelling, Analysis, Predictions, and Projections - MAPP), and SEFSC/SERO base funding. Given the continued importance of climate change and likely increasing impacts, dedicated and consistent funding for climate-priority projects would be beneficial. In the future, requests for proposals could be generated based on priorities identified from RAP actions. For example, since the inception of the RAPs, a priority for headquarters has been CVAs and these have been supported by regional and headquarters leadership. Funding was made available for these activities with the result that CVAs will soon be completed across all NOAA regions. The clear identification of priorities, headquarters and regional support, together with funding availability will be needed to successfully advance additional RAP priorities in the future.

A challenge faced by all Science Centers and Regional Offices is how to use climate science to inform fisheries, protected resources and/or habitat management. It is often the case that more pressing issues take precedence over climate science during day-to-day operations. In the Southeast region, however, there are several examples where the addition of climate-related information improved stock assessments (e.g., Schirripa et al., 2017; Sagarese et al., 2018; Walter et al., 2015) or informed the analyses of UME situations. Despite these successes, the region needs to find more “on ramps” for climate science to enter into the management decision-making process. This may involve presenting the results of climate science studies (i.e., vulnerability assessments and ecosystem status reports) at Council meetings and encouraging the Councils to consider the results of such studies in the development of fishery management actions.

Biological opinions (BOs) serve an important role in consultations under Section 7 (a)(2) of the ESA. SERO Protected Resources Division (PRD) began incorporating climate change data/projections into relevant sections of the BOs. For instance, climate data inform Status of Species and Critical Habitat sections as well as Environmental Baseline and Cumulative Effects sections - all of which decide the Jeopardy/Adverse Modification determinations in the BOs. SERO PRD needs a dedicated and consistent approach to incorporating climate data (e.g., vulnerability assessments, forecasts of climate stressors such as sea level rise [SLR], etc.) into BOs. Ideally, this would facilitate movement toward modeling climate stressors such as SLR in order to forecast impacts to critical habitat (e.g., impacts to smalltooth sawfish of red mangrove loss due to SLR adjacent to armored shorelines).

The development of a formal Gulf and SEUSCS climate team was a high priority action in both RAPs. A Southeast Regional Climate Team would include SEFSC, AOML, HMS, and SERO participants and others with regular meetings and communications. The team would help advise on climate policy and their collaborative expertise would be better able to respond to climate priorities and potentially compete for larger amounts of funding for climate science in the region. Although progress has been made toward establishing a robust climate team, further development of a climate team remains a high and critical priority.

Overall, the Southeast region (both the Gulf and SEUSCS) has made considerable progress across a number of high priority areas, resulting in 16 publications that addressed NCSS objectives (Figure 7.2). In those areas where direct funding was available (e.g., the climate vulnerability analyses), focused effort pushed the projects to either completion or nearing completion. However, the Southeast also made notable progress in unfunded areas. For instance, the incorporation of AMO, ENSO, and the phenology of the seasons into stock assessments, shelf productivity investigations, the SEUSCS ESR, and examinations of growth rates across fish species, respectively, were remarkable efforts that were either base-funded or relied on funding from other sources (e.g., SAIP).

The Southeast region does have specific challenges with respect to applied climate science. The climate signal is not yet as pronounced as in the Bering Sea or the NEUSCS, and so other issues currently take precedence. This requires a proactive regional climate team finding appropriate avenues to introduce climate science into day-to-day operations in the Southeast region. The most direct paths forward will be to design climate research to generate products that are directly useful in specific applications such as stock assessments, UMEs, BOs, and ESRs. That said, the Scientific and Statistical Committee (SSC) recently (June 2020) recommended to the Council that several future stock assessments take the SEUSCS-CVA into account, suggesting some on-ramps for the inclusion of climate science in the management arena do currently exist.

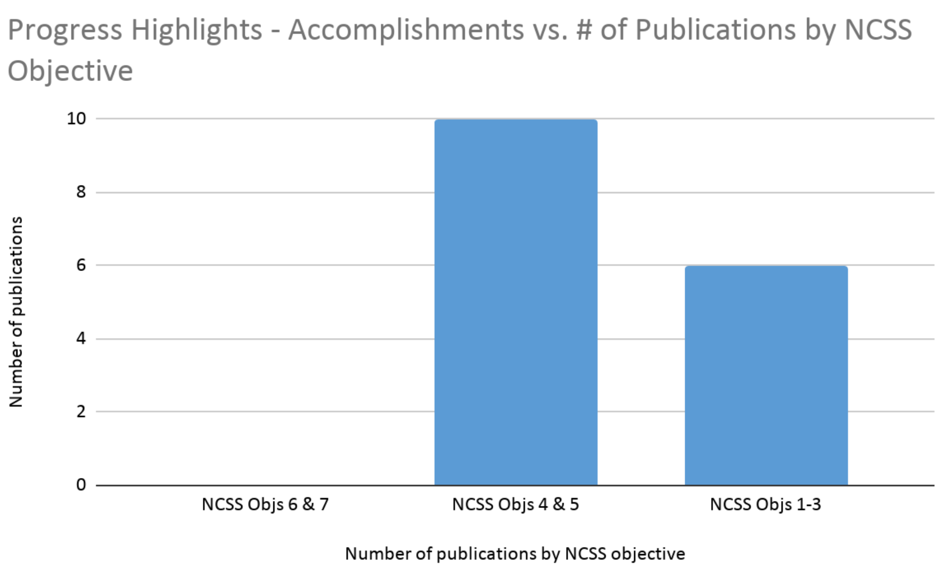

Figure 7.2. Number of RAP-related publications distributed by NCSS objective.

In moving forward, the Southeast region needs to secure more direct funding for climate science, identify a relatively small number of high-priority, achievable actions for its RAPs, and work to develop a larger, more integrated applied research community that addresses regional needs.

7.4 Acknowledgements

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Appendix A - Publications by Objectives

Maintaining Infrastructure and Tracking Change (NCSS Objs 6 & 7)
No publications

Understanding Mechanisms and Projecting Future Conditions (NCSS Objs 4 & 5)

Chagaris, D.S. et al. 2019. Management challenges are opportunities for fisheries ecosystem models in the Gulf of Mexico. Mar. Pol. 101:1-7. https://doi.org/10.1016/j.marpol.2018.11.033

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Informing Management (NCSS Objs 1-3)

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8. Northeast Regional Action Plan

8.1 Introduction

Since the publication of the Northeast Regional Action Plan (NERAP; Hare et al., 2016a) in December of 2016, the Northeast Fisheries Science Center, Greater Atlantic Regional Fisheries Office, and the NOAA Chesapeake Bay Office (NCBO) have made substantial progress at addressing the identified 15 priority actions. The 15 NERAP actions are:

- NERAP Action 1 - Give greater emphasis to climate-related Terms of Reference (TORs) and analyses in stock assessments.
- NERAP Action 2 - Continue development of stock assessment models that include environmental terms (e.g., temperature, ocean acidification).
- NERAP Action 3 - Develop climate- related products and decision support tools to support protected species assessments and other management actions.
- NERAP Action 4 - Increase social and economic scientist involvement in climate change research through multidisciplinary work on climate that includes both social and natural sciences.
- NERAP Action 5 - Develop Management Strategy Evaluation capability to examine the effect of different management strategies under climate change.
- NERAP Action 6 - Improve spatial management of living marine resources through an increased understanding of spatial and temporal distributions, migration, and phenology.
- NERAP Action 7 - Continue to build industry-based fisheries and ocean observing capabilities and use information to develop more adaptive management.
- NERAP Action 8 - Work with NOAA Oceanic and Atmospheric Research (OAR) and academic scientists to develop short-term (day to year) and medium-term (year to decade) living marine resource forecasting products.
- NERAP Action 9 - Work with NOAA Oceanic and Atmospheric Research (OAR) and academic scientists to develop and improve regional hindcasts and climatologies.
- NERAP Action 10 - Conduct research on the mechanistic effects of multiple climate factors on living marine resources with a goal of improving assessments and scientific advice provided to managers.
- NERAP Action 11 - Develop and implement vulnerability assessments in the Northeast U.S. Shelf Region.
- NERAP Action 12 - Continue production of the NEFSC Ecosystem Status Report, and other related products, and improve the distribution of information from the reports through the formation of an NEFSC Environmental Data Center.
- NERAP Action 13 – Maintain ecosystem survey effort in the Northeast U.S. Shelf ecosystem including the Bottom Trawl Survey, Ecosystem Monitoring Program, Sea Scallop Survey, Northern Shrimp Survey, Clam Survey, and Protected Species Surveys and expand where possible (e.g., data-poor species).
- NERAP Action 14 – Initiate a Northeast Climate Science Strategy Steering Group (NECSSSG) to coordinate, communicate, facilitate, and report on issues related to climate change and living marine resource management.

- NERAP Action 15 – Coordinate with other NOAA Programs to link living marine resource science and management to climate science and research activities.

The following sections highlight the progress that has been made on these 15 NERAP actions relative to the NCSS objectives from 2016 to 2020. Highlights of these accomplishments are listed in Table 8.1.

Table 8.1. A selection of NERAP activities grouped by NCSS objective.

Informing Management (NCSS Obj. 1 – 3) • Climate scenario planning for Atlantic salmon and North Atlantic right whales • Northeast Climate Integrated Modeling (NCLIM) Synthesis • Coupling groundfish distribution models with economic models to assess community vulnerability • Investigating potential climate induced prey changes for right whales in southern New England • Development of robust management strategies for NE groundfish fisheries • Progress on climate-enhanced stock assessment variables • Climate-related ToRs in assessments approved by NRCC • Support inclusion of climate information in fishery management decisions • Range-wide Atlantic salmon habitat analysis • Professional learning opportunities for educators in the Chesapeake region
Understanding Mechanisms and Projecting Future Conditions (NCSS Obj. 4 & 5) • Biological effects of ocean acidification in finfish • Expanding capacity for finfish aquaculture research • Research on ocean acidification effects on oysters, surf clam, and sea scallops • Estimating climate effects on production, trophy and phenology of NE groundfish • Black sea bass and spiny dogfish metabolic laboratory studies • New species distribution models based on physical variables • High-resolution spatial modeling of lobster and scallop habitat in the NE • Chesapeake Bay downscaling/forecasting • Seasonal-to-interannual statistical forecasting system for ocean conditions and LMRs • Modeling impacts on the NE U.S. marine ecosystem using ATLANTIS
Infrastructure and Tracking Change (NCSS Obj. 6 & 7) • Maintained EcoMon and living marine resource surveys (fish, shellfish, protected species) • Continued to assess new surveys (Gulf of Maine longline) • Continued ocean acidification monitoring • Formed the NE Fisheries Climate Science Team and developed a climate web-page • Increased interactions with DFO • Continued production of NEFSC State of the Ecosystem reports • Fish and invertebrate Climate Vulnerability Assessment • Tracked changes in ocean conditions, species distributions, phenology and productivity • Investigated changes in river channel geometry in the NE • Historical changes in the number of extreme floods in the US

8.2 Activities and Progress

Build and Maintain Infrastructure (Objective 7)

Goals: NERAP actions 13-15.

Activities – highlights:

- Maintain EcoMon and living marine resource surveys (fish, shellfish, protected species).
- Continue to assess new surveys (Gulf of Maine longline survey)
- Continued Ocean Acidification Monitoring
- Optimization of phytoplankton functional type algorithms for VIIRS ocean color data in the Northeast U.S. Continental Shelf Ecosystem
- Northeast-Southeast Climate/Fisheries Workshop
- Continue to develop NEFSC, GARFO, OHC Matrix Watershed Program for Northeast
- Strengthen links to NOAA Fisheries Habitat programs
- Increase climate literacy among GARFO, NEFSC
- Continue tribal engagement
- Conduct Northeast Climate Integrated Modeling (NCLIM) synthesis meeting
- Increase interactions with DFO (e.g., WGNARS, TMGC)
- Expand collaboration with industry
- Coordinate with North Atlantic Regional Team and Eastern Regional Climate Team)
- Form the Northeast Fisheries Climate Science Team
- Develop a U.S. Northeast climate change webpage
- Develop the capacity to monitor the distribution and abundance of marine species with environmental DNA, boosted by an agency strategic initiative in genomics (Liu et al., 2019)

Progress summary

While the NEFSC has maintained its critical surveys, there has been a decline in the number of days at sea available, which has led to a decrease in the amount of data being collected (Figure 8.1). This is a major concern given that both the trend and variability of ocean temperature within the U.S. Northeast Large Marine Ecosystem have been increasing. These changes in the ocean have been associated with abundance and distribution shifts in the living marine resources of the region. Therefore, it is critical that we not only maintain our surveys but also increase the number of days at sea in order to effectively track changes in the ocean both seasonally and annually. Due to the COVID-19 pandemic, NEFSC surveys were impacted for the spring and summer of 2020, resulting in substantial data gaps (Figure 8.1). Ocean acidification monitoring is still limited spatially and temporally; we are considering proposals to enhance our sampling. The use of satellite data is essential for increasing the spatial and temporal coverage of ocean data. Progress has been made towards regional optimization of phytoplankton size class/functional type algorithms and long-term trend analyses of the 20+ year time series of ocean color data.

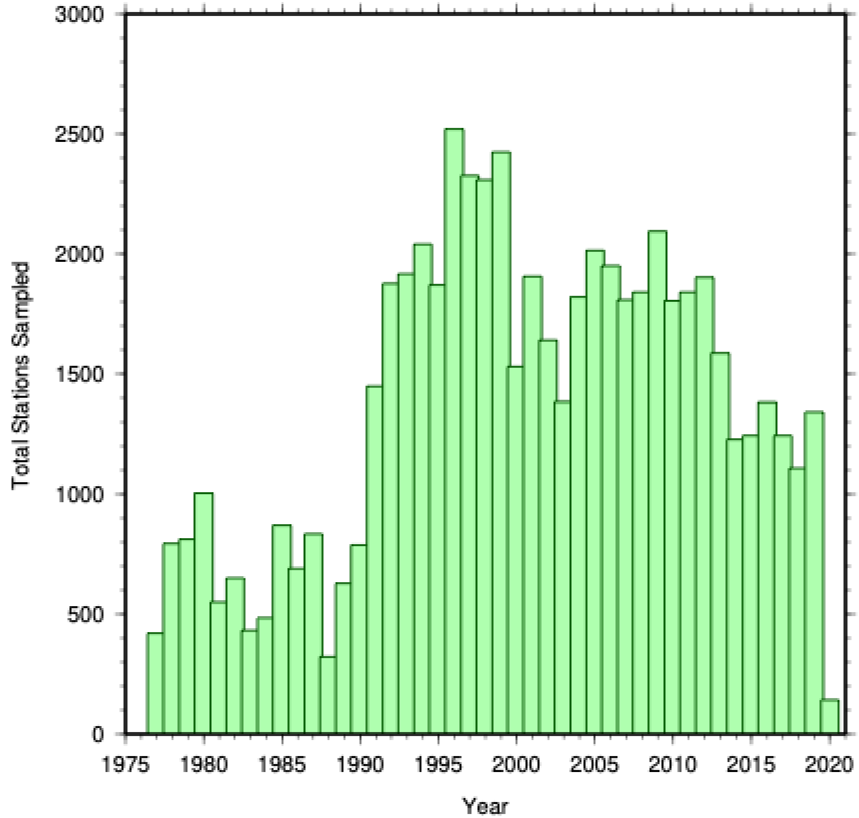

Figure 8.1. Number of ocean stations sampled each year by NOAA NEFSC surveys (EcoMon, trawl, MARMAP, scallop, protected species, etc.).

The Northeast-Southeast Data Coordination Workshop was postponed to 2021 due to the travel restrictions in 2020. We have continued to coordinate with the NWFSC Watershed Program director and staff from NEFSC, GARFO, and HQ to best leverage current capacity to develop a matrix watershed program for the Northeast, further developing summary documents and synthesis materials through bi-monthly or quarterly meetings.

Scientists within the NEFSC have collaborated with academic and NGO groups on various NERAP related projects. The majority of these projects are funded by various NOAA programs but also stem from NASA, Lenfest, and NSF. Some of our key academic and NGO partners include the Woods Hole Oceanographic Institute, Gulf of Maine Research Institute, University of Massachusetts, Rutgers University, University of Connecticut, Stony Brook, Princeton University, University of Rhode Island, and Monmouth University. Increased collaborations with Fisheries and Oceans Canada (DFO) has also occurred and resulted in peer-reviewed publications (Greenan et al., 2019, Richardson et al., 2020).

The recently formed Northeast Climate Science Team can fulfill several roles in advancing the ongoing climate science work of the NEFSC and GARFO. These would include: promote integration of various climate science activities across the NEFSC and GARFO; coordinate strategic engagement with partners; promote awareness of NEFSC, GARFO, and partner-based climate science activities; track progress toward climate science goals; be a representative body of the region's climate science community; interface with NOAA leadership on climate science work, support, and prioritization; and target relevant funding opportunities toward NERAP priorities. We are tracking and communicating our climate research through our ecosystems and climate change webpage[45] and the New England groundfish in a changing climate webpage[46].

Tracking Change (Objective 6)

Goals: NERAP actions 11-12.

Activities – highlights

- Continue production of NEFSC State of the Ecosystem Reports.
- Develop climate vulnerability assessments
- Track changes in ocean conditions, species distribution and abundance, ecosystem changes, phenology, and productivity
- Investigating changes in river channel geometry in the Northeast U.S. associated with historical changes in flood magnitude and frequency
- Historical changes in the number of extreme floods in the United States

Progress summary

The Ecosystem Dynamics and Assessment Branch has been leading the development of the State of the Ecosystems Reports[47] for the New England and Mid-Atlantic regions. The latest reports for 2020 have been completed for New England (Gulf of Maine/Georges Bank) and the Mid-Atlantic (Middle Atlantic Bight). Some of the key findings in the 2020 reports were:

1. Since 2000, the proportion of energy removed by fisheries has been declining. In the Mid-Atlantic, commercial landings have declined while primary production has remained steady. In New England, commercial landings have been steady while primary production has increased slightly.

2. Engagement in commercial fishing has been declining since 2004 for medium to highly engaged Mid-Atlantic fishing communities. Conversely, engagement is increasing in New England for moderately engaged fishing communities.

3. In New England, two single-species commercial fisheries—Gulf of Maine lobster and Georges Bank scallops—account for a majority of catch and revenue. Relying on single-species fisheries can be a risk to fishing communities if these populations decline.

4. Fish habitat modeling indicates which species are most likely to be found in current and proposed wind energy lease areas. For the Mid-Atlantic managed species, summer

[45] https://www.fisheries.noaa.gov/new-england-mid-atlantic/climate/climate-change-northeast-us-shelf-ecosystem
[46] https://www.fisheries.noaa.gov/new-england-mid-atlantic/science-data/new-englands-groundfish-changing-climate
[47] State of the Ecosystem Reports website - https://www.fisheries.noaa.gov/new-england-mid-atlantic/ecosystems/state-ecosystem-reports-northeast-us-shelf

flounder, butterfish, longfin squid, and spiny dogfish top the list. For New England managed species, Atlantic herring, little skate, winter skate, windowpane flounder, and winter flounder rank highest.

5. Over the last decade, marine heatwaves have increased in intensity and duration throughout the region. Temperatures at the bottom of the ocean are also warming.

6. Coastal habitats are under stress in the Mid-Atlantic. Heavy rains in 2018-2019 degraded Chesapeake Bay water quality, increasing oyster mortality and spreading invasive catfish. Sea-level rise is also altering coastal habitats, driving declines in nesting seabirds on Virginia islands.

7. The Gulf Stream is shifting northward and is increasingly unstable, producing more warm core rings. These smaller-scale eddies break off from larger ocean currents, rotate clockwise in a ring, and circulate warm Gulf Stream water within the Northeast Shelf Ecosystem. The result is a higher likelihood of warm salty water and the appearance of associated oceanic species such as shortfin squid on the shelf.

8. During the last three years, the source waters flowing into the Gulf of Maine have been dominated by warm offshore waters associated with the Gulf Stream. In comparison to the past, almost no cold waters originating from the Labrador Current have entered the Gulf of Maine. The changing proportions of source water affect the temperature, salinity, and nutrient inputs to the gulf.

The metadata for these reports is documented every year and is also published as a stand-alone document (https://noaa-edab.github.io/tech-doc).

The observed change in ocean surface temperature in the shelf and slope seas has been analyzed in terms of the trend and variability suggesting about one third of the warming is likely due to anthropogenic factors (Chen et al., 2020). The warming on the shelf can be manifested as marine heatwaves caused by advection at the shelf break exchange (Gawarkiewicz et al., 2019). Ocean bottom temperature has also warmed throughout the region (Friedland et al., 2020a).

The warming in both the surface and bottom ocean layers has led to a northeasterly shift in the distribution of finfish and invertebrates (Friedland et al., 2019) and an increase in diversity and productivity of the U.S. Northeast Shelf ecosystem (Friedland et al., 2020b). A sub-regional analysis suggested that northeastern shifts were dominant in the Mid-Atlantic Bight and Georges Bank while southwestern shifts into deeper water dominated in the Gulf of Maine (Kleisner et al., 2016). Gulf of Maine phenological shifts in both physical and biological events have been shifting to earlier timing, observed in spring onset, spring and winter hydrology, zooplankton abundance, occurrence of several larval fishes, and diadromous fish migrations (Staudinger et al., 2019). Later timing was documented for fall onset, reproduction and fledging in Atlantic puffins, spring and fall phytoplankton blooms, and occurrence of additional larval fishes (Staudinger et al., 2019). Regime shifts in zooplankton communities have occurred over the last three decades and are associated with warming ocean temperature, stratification, and decadal climate variability (Morse et al., 2017). These shifts in zooplankton communities were also linked to regime shifts in fish recruitment, which was a function of copepod abundance and structure (Perretti et al., 2017), suggesting further evidence of climate impacts on recruitment. Work on the synergistic effects of fishing and ocean warming on groundfish habitat suggest that fishing pressure also plays a large role in the observed shifts in species distributions (Adams et al., 2018).

Ocean acidification is being monitored in both shelf and coastal waters where shellfish aquaculture is vulnerable to the continued decrease in ocean pH (Poach et al., 2019). Carbonate chemistry at the sediment surface in Long Island Sound demonstrated seasonal variability during the summer months (Meseck et al., 2018). Aragonite saturation states varied between 0.5 and 1.6, mostly well below a saturation state of 1.5, which is considered a critical threshold for marine organisms (Seidlecki et al., 2021).

Single species research has also been conducted in relation to this observed warming trend. Results document a northeastern shift in the spawning distribution and biomass of a key forage fish, Atlantic mackerel (McManus et al., 2017; Richardson et al., 2020); northern shifts in the distribution of four baleen whale species since 2010 (Davis et al., 2020); a decrease in American lobster habitat in southern New England and an increase in the Gulf of Maine with an offshore movement (Tanaka et al., 2019; Mazur et al., 2020); and a northern shift in black sea bass spawning and settlement into the southern Gulf of Maine (McBride et al., 2018).

In collaboration with our international partners, we have gained further insight into the large scale oceanic teleconnections causing both the observed and projected warming of the Northwest Atlantic (Chen et al. 2020). This work resulted in a publication in the journal *Nature* (Caesar et al., 2018) and it associated the dichotomy of enhanced warming in the Northwest Atlantic with enhanced cooling the North Atlantic subpolar gyre to a weakening Atlantic Meridional Overturning Circulation[48].

The seasonality and trends of river floods in the New England and Middle Atlantic regions have been analyzed and results suggest that warm-season flood potential has increased with possible implications for aquatic and riparian organisms (Collins et al., 2019).

The U.S. Northeast Fish and Invertebrate Climate Vulnerability Assessment (CVA) was completed and published in 2016 (Hare et al., 2016b). This assessment of 82 species found that overall climate vulnerability is high to very high for approximately half the species assessed; diadromous and benthic invertebrate species exhibit the greatest vulnerability. In addition, the majority of species included in the assessment have a high potential for a change in distribution in response to projected changes in climate. Negative effects of climate change are expected for approximately half of the species assessed, but some species are expected to be positively affected (e.g., increase in productivity or move into the region).

A social vulnerability assessment was also completed for the eastern and Gulf of Mexico coast regions of the U.S. (Colburn et al., 2016). This work used Community Social Vulnerability Indicators to assess the impacts of sea level rise on commercial fishing infrastructure and

[48] Webstory on weakening circulation - https://www.fisheries.noaa.gov/feature-story/reconstruction-major-north-atlantic-circulation-system-shows-weakening

species dependence. Results showed that for fishing communities with nearshore infrastructure, the impacts from sea level rise can be even greater if the local economy is dependent upon a particular ocean-related industry or ocean species and/or is socially vulnerable. Low catch diversity introduces other risks that fishing communities must consider.

The U.S. Northeast Habitat CVA is currently in its final phase of development. Staff from both the NEFSC and GARFO have also participated in the marine mammal and sea turtle climate vulnerability assessments (in progress).

Understanding Mechanisms (Objective 5)

Goals: NERAP Action 10.

Activities – highlights:

- Biological effects of ocean acidification in finfish
- Data synthesis via dynamic models of ocean acidification effects in winter flounder
- Experimental evaluation of biological effects of thermal regimes on key early life-stage parameters in summer flounder
- Estimating climate effects on production, trophic interactions, and phenology of NE groundfish
- Expanding capacity for finfish aquaculture research to support regulatory streamlining in Northeast U.S.
- Continue research on ocean acidification effects on oysters, surf clam, and sea scallops
- Black sea bass and spiny dogfish metabolic studies at Sandy Hook

Progress summary

The NEFSC's Milford and Sandy Hook laboratories have been at the forefront of laboratory based process studies that analyze the mechanistic underpinnings between biophysical changes in the oceans and living marine resources in the U.S. Northeast. The Milford lab primarily focuses on invertebrates while Sandy Hook focuses on finfish and some invertebrates.

Research projects in collaboration with some of our academic partners have analyzed the impacts of changing water temperature on black sea bass aerobic scope and hypoxia tolerance (Slesinger et al., 2019); physiological processes for bivalves under ocean acidification conditions; estimates of CO_2 and co-stressor effects on early life-stages of finfish such as winter flounder, summer flounder, Mid Atlantic forage fishes, and New England groundfish; individual-based process models of CO_2 effects on winter flounder; dynamic energy budget model of physiological processes for bivalves under ocean acidification conditions and different temperatures; different populations and multi-generationally exposure of bivalves to OA .

Regarding experimental studies of biological effects of climate and OA in finfish, the NEFSC Sandy Hook Lab has developed novel apparatus for testing plasticity of responses to thermal, CO_2, and dissolved oxygen regimes. These studies, which use over a dozen different treatment levels – including variable ones – are revealing the functional form of critical rate processes that would not be revealed in simpler (fewer treatment level) designs. These data-supported functions capture how rate processes are affected by environmental drivers and are precisely the kinds of quantitative descriptions needed to model consequences at the population and higher levels.

With respect to bivalve research and OA, research has focused on the larval and juvenile stage. For the larval phase, changes in growth, % metamorphosed, and lipid composition was observed with a hormetic response for *Spisula solidissima similis*; however there was no difference in survival under OA. Physiological processes (feeding rates) have been documented for two bivalve species - *Mytilus edulis*, blue mussels, and *Spisula solidissima solidissima*, Atlantic surfclams. For blue mussels, feeding rates were negatively affected by increased OA (Meseck et al., 2020) in the laboratory and in the field. Decreased feeding rates were also observed in surfclams. Pousse et al. (2020) also found that Atlantic surfclams had less energy available to grow under OA. The physiological data from Pousse et al. is being used for a dynamic energy budget model on surfclams. In the field, total benthic bivalve abundance in Long Island Sound was correlated to carbonate chemistry parameters (Meseck et al., 2018). These studies demonstrate from the laboratory to the field that bivalves are sensitive to OA.

Projecting Future Conditions (Objective 4)

Goals: NERAP Actions 6-9.

Activities – highlights

- Spatial and seasonal patterns of carbonate chemistry in the Northeast U.S.
- Identify how Chesapeake Bay Interpretive Buoy System can contribute to regional downscaled models and climate indicator development
- Chesapeake Bay downscaling/forecasting
- Develop and pilot a hypoxia vertical profile monitoring design at two locations in the Chesapeake Bay
- Develop and evaluate a seasonal-to-interannual statistical forecasting system for oceanographic conditions and living marine resources in the Northeast U.S.
- Recently funded OAR CPO projects to develop regional hindcasts, forecasts, and projections for the Northwest Atlantic using NOAA's state-of-the-art ocean model MOM6
- Build and analyze new species distribution models based on physical variables beyond ocean temperature
- Modeling Climate Change Impacts on the Northeast U.S using Atlantis
- Modeling responses of New England groundfish to multiple ecological aspects of climate change
- Forecasts of ocean temperature in relation to species distribution forecasts in the Northeast U.S.
- Modeling Habitat Response to Ecosystem Change: Suitability Prediction in the Northeast U.S.
- High-resolution spatial modeling of lobster and scallop habitat in the Northeast U.S.

Progress summary
Presently, the skill of sub-seasonal to seasonal (S2S) sea surface temperature forecasts for the U.S. Northeast shelf is relatively low compared to other large marine ecosystems. The reason for the poor skill in our region is because SST forecasts are derived from global models that have coarse resolution in their ocean and atmosphere components. Tactical fishery and

protected species management can greatly benefit from more skillful S2S forecasts of ocean conditions. There are multiple efforts underway, in collaboration with our academic partners and NOAA OAR, to enhance the S2S forecast skill of ocean temperature (surface and bottom) in the U.S. Northeast and throughout the Northwest Atlantic.

In collaboration with the Woods Hole Oceanographic Institution, statistical forecasting models that use historical ocean and atmospheric data are being developed and tested. Results are promising for specific regions and months of the year. Dynamical approaches are also underway via newly funded projects from NOAA OAR CPO. Our main research will focus on the development and validation of regional model simulations for the Northwest Atlantic using NOAA's state-of-the-art ocean model MOM6 in hindcast, forecast, and projection modes. This work will be in collaboration with NOAA GFDL, Princeton University, and Rutgers University and is directly linked to the NOAA Climate and Fisheries Initiative[49]. Additional research was recently funded to use the Scripps Coupled Ocean-Atmosphere Regional (SCOAR) modeling system to develop annual to decadal ocean forecasts for the U.S. Northeast shelf. These projects will lead to multiple regional modeling simulations for the U.S. Northeast shelf and will enable us to understand which models and simulations are most useful to fisheries and protected species management in our region.

Progress was also made in our estuary modeling research. Estuaries and rivers are critical habitat for many marine species in the U.S. Northeast and thus modeling efforts are critical in order to understand and predict changes associated with climate. Historical model hindcasts of Long Island Sound (Georges et al., 2016; Schulte et al., 2017; Schulte et al., 2018) have been developed and analyzed relative to large scale climate forcing. We have also made progress in our model downscaling efforts for the Chesapeake Bay in terms of hindcasts and projections (Muhling et al., 2017; Muhling et al., 2018).

The NEFSC has collaborated with many academic and non-governmental organizations to develop long-term projections of living marine resource habitat change using NOAA's prototype high-resolution global climate model CM2.6. This model has been used extensively over the last five years due its very high-resolution ocean component (10-km) that resolves the very fine scale bathymetry and regional circulation of the U.S. Northeast shelf (Saba et al., 2016). Global models assessed by the IPCC's fifth report do not resolve these regional features that are critical to the ocean dynamics of the U.S. Northeast shelf.

This body of work includes the projected impacts of climate change on the habitat of two of the most valuable U.S. fisheries, sea scallops and American lobster. Our research suggests that both of these species may be negatively impacted by continued warming in the Northwest Atlantic (Tanaka et al., 2020). Other research using high-resolution projections of ocean change has focused on a large suite of marine taxa observed in our fall/spring bottom trawl survey (Kleisner et al., 2017; McHenry et al., 2019), as well as single species studies comprising American lobster in Canadian waters (Greenan et al., 2019), cobia in the U.S. east coast (Crear et al., 2020), cod and spiny dogfish (Selden et al., 2018), and *Calanus* zooplankton (Grieve et al., 2017).

[49] https://www.fisheries.noaa.gov/topic/climate-change#noaa-climate-and-fisheries-initiative

The projected impacts of ocean temperature (Tanaka et al., 2020) and acidification (Rheuban et al., 2018) on sea scallops have been studied in separate analyses, each indicating a decline in biomass or habitat over the next century.

We are developing a new version of our end-to-end ecosystem model (ATLANTIS-NEUS). Presently, we are forcing the model with satellite-based primary production and physics from global reanalysis products (GLORYS). We plan on incorporating forcing from a high-resolution regional ocean model with biogeochemistry from COBALT and with physics from the regional MOM6 model. ATLANTIS-NEUS will be run in hindcast mode (1980-2014) and projection mode (2055-2085), which will allow us to associate both contemporary and projected climate impacts on the entire marine ecosystem of the U.S. Northeast, as well as evaluate different management strategies under climate change

We are also investigating future changes in the abundance and distribution of New England groundfish and have also completed an analysis of 5-year forecasts of SST as indicators of species distribution change. We are developing a modeling package suitable for use in predicting species shifts under various climate change scenarios. Model results will be utilized as a starting point to develop a larger MAFMC program of habitat definition and risk analysis.

NCBO is supporting a study characterizing habitat utilization of two valuable fisheries species along the southern Mid-Atlantic Bight: black sea bass (*Centropristis striata*) and summer flounder (*Paralichthys dentatus*). Understanding the habitat preferences of these species and quantifying the relationships between habitat use and environmental factors will provide insight into potential population responses to climate change (e.g., increased water temperatures).

Informing management (Objectives 1 - 3)

Goals: NERAP Actions 1-5.

Activities – highlights

- Climate scenario planning for Atlantic salmon and North Atlantic right whales
- Investigating potential climate induced prey changes for right whales in southern New England
- Range-wide Atlantic salmon habitat analysis
- Identifying cold water refugia for Atlantic salmon in distinct population segment watersheds
- Participate in the Marine Mammal and Sea Turtle Climate Vulnerability Assessments
- Conservation of Atlantic Sea Turtles Project: Fisheries Bycatch Mitigation
- Development of robust management strategies for northeast groundfish fisheries in a changing climate
- Coupling climate and groundfish species distribution models with economic models of fishing location decisions to assess community vulnerability
- Continued social indicators work
- Northeast Climate Integrated Modeling (NCLIM) synthesis
- Provide educational programming for Ocean Acidification Citizen/Student Science Project

- Provide professional learning opportunities for educators in the Chesapeake region focused on climate change and resilience
- Continue discussions on NEPA and climate decisions
- Extending single-species state-space assessment models to incorporate environmental effects on life-history attributes
- Conduct community resiliency engagement (GARFO)
- Climate-related TORs in assessments approved by the Northeast Region Coordinating Council (NRCC)
- Support NEFMC, MAFMC, and ASMFC inclusion of best available climate information in fishery management decisions

Progress summary
Climate scenario planning initiatives and summary reports were completed for endangered North Atlantic right whales and Atlantic salmon. The report for salmon was published (Borggaard et al., 2019) along with the right whale report (Borggaard et al., 2020). A range-wide salmon habitat synthesis is ongoing and will describe habitat conditions suitable (including preferences and tolerances) for Atlantic salmon by life stage in freshwater and marine systems. This manuscript will be completed in fall 2020. Restoring and maintaining access to high quality freshwater and estuarine habitats in Maine is a focus of Atlantic salmon recovery efforts. NOAA is contracted with USGS to identify stream reaches in Salmon Habitat Recovery Units (SHRUs) in Eastern Maine watersheds that have substantial groundwater inputs and thus are likely to be colder than reaches that do not. These stream reaches can provide high quality salmon nursery habitat and thermal refugia. Initial analyses will be completed in fall 2020 and partners are looking for funding to project stream temperature conditions in the SHRUs under future climate scenarios.

Over the last two years we have used NERAP funds from NMFS S&T to conduct short duration zooplankton sampling trips in the southern New England region during the winter and early spring (January – April) of 2019 and 2020 when right whales are in the area. Our goal is to describe vertical distribution patterns of right whale prey in relation to physical features to better understand the mesoscale processes that result in super aggregations of right whale prey. Correlations between ocean warming and right whale prey availability suggest an inverse relationship between *Calanus* spp. and ocean temperature (Sorochan et al., 2019).

Staff from GARFO and the NEFSC have participated in the climate vulnerability assessments of marine mammals and sea turtles. We have also made substantial progress on an analysis that projects changes in loggerhead sea turtle habitat based on high-resolution archival tagging data. Similar research is being conducted on leatherback turtles that uses NOAA's high-resolution global climate model. Models for cetaceans have been developed that use environmental variables to predict habitat suitability and abundance, two metrics that can support conservation management decisions and marine spatial planning (Chavez-Rosales et al., 2019).

Further progress has been made on our social sciences research. We have developed simulation models that address various climate impacts to single species and have evaluated climate informed reference points. This work is coupled to new research that links climate- and stock-related projections for groundfish to economic outcomes for fishermen and fishing communities. We are constructing statistical models that explain how fishermen select target stocks and landing locations. These models can then be used to understand how these two behaviors will change under various climate and policy scenarios. Other social sciences research that has been funded by the New England groundfish/climate program[50] includes: climate vulnerabilities and adaptation pathways for Northeast U.S. fishing communities; stakeholder engagement in management strategy evaluation of New England groundfish in a changing ocean; and developing indices of vulnerability to climate change for groundfish fishing communities in the Northeast.

Progress on climate-enhanced stock assessment variables (e.g., demographics, recruitment, population growth) has also been moving forward on key commercial and recreational species including southern New England yellowtail flounder (Miller et al., 2016a; Xu et al., 2017), summer flounder (O'Leary et al., 2018; O'Leary et al. 2020), winter flounder (7), northern shrimp (Cao et al., 2017), Atlantic cod (Miller et al., 2018), surf clam (Hennen et al., 2018), and black sea bass (Miller et al., 2016b). We have also developed a framework for incorporating climate and habitat information into fisheries management using risk assessment and management strategy evaluation (Gaichas et al., 2016). Support was provided to the MAFMC risk assessment (Gaichas et al., 2018), which included the results from the climate vulnerability analysis and habitat shifts into a conceptual model for high risk summer flounder fisheries in 2019.

NCBO leads the Climate Resiliency Workgroup of the Chesapeake Bay Program (CBP) providing climate-related planning and implementation with partners in the watershed through improving monitoring, resiliency, and adaptation. For example, NOAA completed a climate vulnerability assessment used by the Town of Oxford, Maryland--located in the NOAA Choptank Habitat Focus Area--to develop adaptation solutions. NCBO is working through CBP to develop a suite of climate indicators and investigate how water-quality best management practices will be affected by climate change.

NCBO partnered with Virginia Institute of Marine Science researcher Emily Rivest to support a student focused citizen science and education program looking at carbonate chemistry and oyster growth. High School students in Virginia (Chesapeake Bay Governor's School) and Maryland (St. Michael's High School) monitored water chemistry and oyster growth throughout the school year and the Rivest lab used this data to develop an understanding of baseline conditions and oyster growth rates in these two systems. Students reported learning about the current and future impacts of a changing climate on the Chesapeake and in particular oysters, via ocean acidification.

The NCBO's Environmental Literacy Team has hosted 10 workshops on the topic of climate change and resilience since 2017. These workshops fall into two participant categories:

1. Non-formal Educator Professional Development - mostly non-formal educators from organizations like environmental education centers, aquariums, museums, and universities who regularly provide programming for both teachers and students. These

[50] https://www.fisheries.noaa.gov/new-england-mid-atlantic/science-data/new-englands-groundfish-changing-climate#2019-social-science-projects

workshops provide climate science content and project-based approaches to incorporating these concepts into existing and new programing.
2. Formal Educator Professional Development - K-12 teachers from public and private schools. These workshops provide opportunities for teachers to learn about climate science and opportunities to deliver it through standards-based instruction.

This past June NCBO and partners facilitated the inaugural Mid-Atlantic Climate Change Education Conference. This conference provided an opportunity for 300 regional educators to explore climate change topics and learn about climate education practices being implemented throughout the region.

8.3 Conclusions

Since 2016, we have published 59 peer-reviewed manuscripts that focus on the U.S. Northeast marine ecosystem and directly address the seven NCSS objectives (Figure 8.2). These publications were either authored or co-authored by NEFSC, GARFO, and NCBO staff. Table 8.1 lists the top ten accomplishments. We have conducted both multi-species and single species focused research on both contemporary and projected climate impacts. Climate vulnerability assessments for fish, invertebrates, sea turtles, and marine mammals have been completed. Our work on human dimensions, particularly on social vulnerability to climate change, has also been progressing and continues to be developed. Understanding the vulnerability of fishing communities and fishing infrastructure to climate change is a core component of our NERAP research, which is being led by the NEFSC social sciences branch.

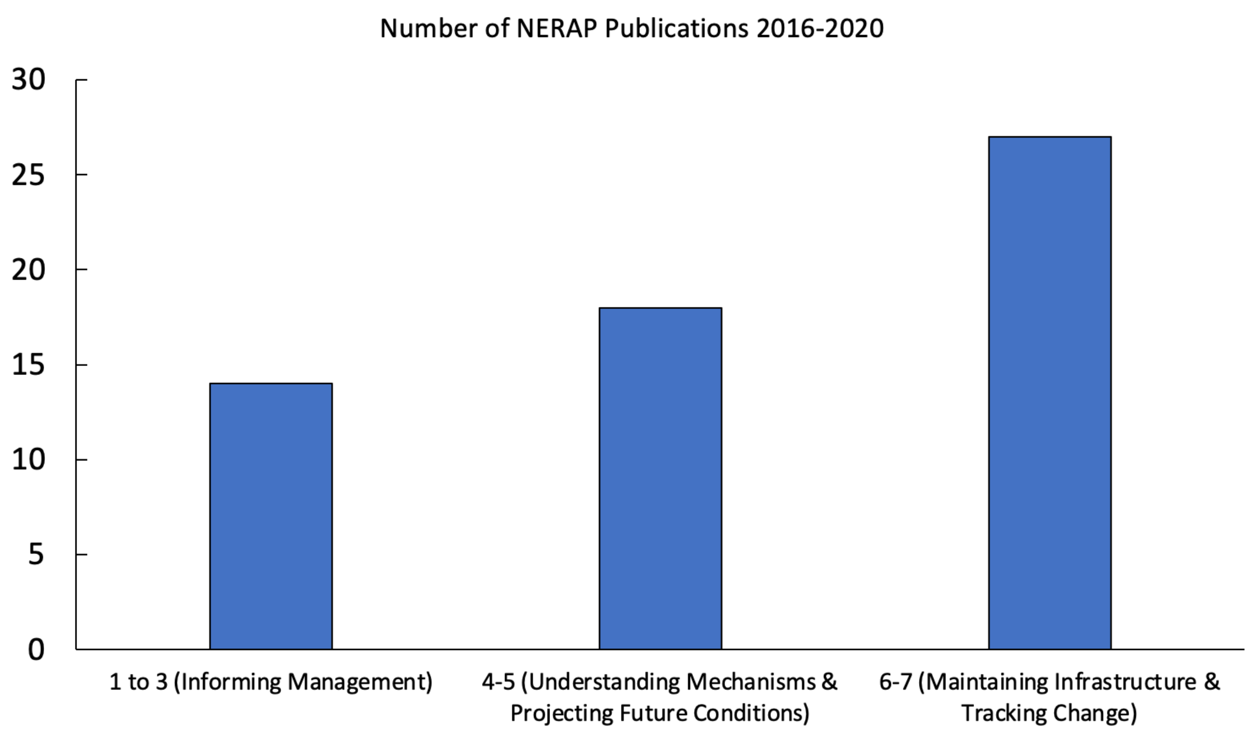

Figure 8.2. Number of NEFSC, GARFO, and NCBO peer-reviewed publications from 2016-2020 that address the seven NCSS objectives and fifteen NERAP priorities.

The climate vulnerability assessment for U.S. Northeast habitat will be completed this year. Climate scenario planning for Atlantic salmon and North Atlantic right whales has been proven to be very informative and we plan on continuing these exercises. These efforts have also served as a model for others (e.g., see April 2020 presentation at Mid-Atlantic Fishery Management Council). Our laboratory research on invertebrates and finfish is a critical component of our climate research that must continue in order to inform models that are developed to assess the impacts of a changing ocean environment on various life history traits.

Projections of future change have largely focused on marine species habitat and distribution using NOAA's high-resolution global climate model. While these longer term projections (20-80 years) could be useful for fishery management plans or management strategy evaluations over decadal periods, they are not useful for tactical management decisions that are made on a year to year basis. Seasonal to annual (S2A) forecasts of ocean conditions that are tied to stock assessments would be more useful to tactical fisheries management. However, the skill of ocean forecasting models for even the most standard ocean variable, sea surface temperature, is relatively low in the U.S. Northeast marine ecosystem compared to other coastal large marine ecosystems. Therefore, we have started to focus more of our efforts on improving the S2A skill of ocean forecasts for the region. Through NOAA funding, we have collaborated with our academic partners to develop a statistical forecasting framework for the region. We have also started the process of the dynamical approach, which is to develop regional ocean models for the Northwest Atlantic that can run in hindcast, forecast, and projection mode. This dynamical approach directly addresses the recent NOAA Climate and Fisheries Initiative[51] and our goal is to have multiple regional ocean model simulations for the region that are based on NOAA's state-of-the-art ocean model MOM6. We have also recently received NOAA funding to develop annual to decadal ocean forecasts using the Scripps Coupled Ocean-Atmosphere Regional (SCOAR) modeling system.

One of the most critical components of our NERAP work is to make progress on climate enhanced stock assessment variables (e.g. recruitment, mortality, growth). This research is needed in order to apply historical, forecasted, and projected climate information to stock assessments and ultimately inform management. It will also help us move beyond species distribution and habitat projections and allow for biomass and abundance modeling. We have developed new models for seven commercial and recreational fish and shellfish stocks. More research is needed to address other stock assessment variables and we need to include more commercial, recreational, and protected species. Our laboratory based process studies are an essential component of this research and more mechanistic studies are needed to inform models that use climate information (i.e., temperature, ocean pH) to predict life history trait variability.

None of our NERAP research can be successful without a solid infrastructure for ocean observations. This includes both physical and biological surveys. We are concerned about the decline in our number of observations per year, which is a direct result of our declining number of days at sea (Figure 8.1). This observation decline is occurring at a time of both increasing trend and variability of many ocean and biological variables. Skillful models, whether for single species or the entire ocean ecosystem, including human dimensions, can only be developed if

[51] NOAA Climate and Fisheries Initiative website - https://www.fisheries.noaa.gov/topic/climate-change#noaa-climate-and-fisheries-initiative

observations exist over sufficient temporal and spatial scales that capture seasonal, annual, and decadal variability.

Our main goal moving forward is to conduct more focused research that can inform and enhance living marine resource tactical management decisions. This is a very challenging task not just for the Northeast region but for all U.S. regions. The Northeast U.S. deals with two Federal management councils along with an Atlantic States Commission, in which the three bodies manage marine species that are all interacting with each other. Moreover, there are very few operational fishery stock assessments in the U.S. and worldwide that use environmental data quantitatively or qualitatively to inform year-to-year management decisions on catch limits. Over the next five years, our goal is to produce research results that support the use of climate and environmental information for upcoming research track stock assessments. We also hope to use future modeling products and tools derived from the NOAA Climate and Fisheries Initiative to accomplish the goal of climate-ready fisheries management in the Northeast U.S.

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9. Summary - Hits, Misses, and Next Steps

Following the release of the NCSS in 2015, one of the first actions was to establish a climate team in each region. The teams consisted of personnel from the Science Centers and Regional Offices who worked with regional partners to develop their Regional Action Plans outlining climate-related goals and activities to reach those goals over the ensuing 3-5 years. As highlighted in the preceding chapters, great progress has been made in each region. Taking stock of the various actions and accomplishments, here we identify areas where the greatest amount of progress has been made, as well as areas that should now or continue to be focal points for further effort. The intent is to identify specific needs that can help to guide the development of an updated set of RAPs (RAP 2.0) for each of the regions that will set goals, identify appropriate metrics, and outline specific actions to be carried out over the next three to five years.

The NCSS originally provided a suite of recommended priority actions to help NOAA Fisheries address its mandates in a changing climate. The actions were grouped into time-frames, with three actions recommended to be adopted and executed first, and others recommended for the "near-term", "medium-term", and "long-term" as resources (time, personnel, funding) allow (see pages 44-47 of the NCSS for the list of actions).

So how did we do? Looking back on the last five years, it is evident that NOAA Fisheries is much better off in terms of the ability to detect, identify, forecast and react to climate-related changes and their impact on the Nation's fisheries and fishery-dependent communities. There is strong scientific infrastructure across the regions that supports the science enterprise needed to fulfill the NOAA Fisheries mandates. This infrastructure has been key to maintaining, and in some cases expanding, fishery and ecosystem surveys and observations needed to track changes and provide early warnings of the impacts of climate change. Close working relationships with federal, state, academic, NGO, and industry partners have also been valuable for leveraging resources for surveys and observations as well as expanding capabilities to conduct additional research and develop indicators to track changes and understand mechanisms. Most regions have developed ecosystem status reports to provide easy access to information on the status of various physical, chemical and biological components of the ecosystem, and their trends over time. Overall, a great deal of progress and success has been achieved on the lower tiers of the NCSS objective pyramid with actions focused on maintaining and improving a strong scientific foundation and the ability to track ecosystem changes (Table 9.1a).

The middle tiers of the NCSS pyramid focus on a better mechanistic understanding of climate impacts on LMRs, developing projections of future climate and ocean conditions, and identifying what species are most vulnerable to current and anticipated climate and ocean conditions. Progress in this realm was good. Climate Vulnerability Assessments (CVAs) for fishery species were conducted in each of the regions, and larger basin-scale assessments were conducted for marine mammals and sea turtles. Other efforts progressed a bit more heterogeneously (see

Table 9.1b). Partnerships between NMFS and OAR through the COCA and MAPP programs helped to provide additional funding for focused research to better understand mechanisms of climate impacts on fisheries and develop regional physical and biological models to improve forecasts. Initial funding was focused in a few regions (NE, Bering Sea, West Coast) and has been expanding to other regions.

Ultimately, the goal of the NCSS is to provide the necessary science and information to support the needs of managers working to sustainably manage living marine resources in a changing climate. The top tiers of the NCSS pyramid (Figure 1.1) address this goal. Progress in these upper tiers is dependent upon the lower tiers, and has been relatively limited (see Table 9.1c) as most of the effort has been in building and strengthening the supporting science. One of the priority actions for helping to better inform management was to build capacity to conduct management strategy evaluations (MSEs). This is similarly a priority highlighted in the NOAA Fisheries Ecosystem-Based Fisheries Management Roadmap (NMFS, 2017) and Next Generation Stock Assessment Improvement Plan (Lynch et al., 2018). Good progress has been made in increasing capacity in each of the regions to conduct MSEs. For example, a promising framework (the Alaska Climate Integrated Modeling Project[52]) specifically for evaluating management strategies for changing climate and ocean conditions has been developed and piloted for the Eastern Bering Sea. Efforts are underway to develop similar frameworks in other regions (California Current [Future Seas Project], Gulf of Alaska, Northwest Atlantic).

As stated earlier, NOAA Fisheries has made substantial progress over the last five years towards achieving the goals of the NCSS, but it is clear there is still much to be done. Each region continues to have their own specific goals that account for the types of climate impacts being felt in the region and the resources they have available to address those impacts. However, national efforts to share expertise and other resources across the regions should improve the ability to develop similar capabilities in each region.

This progress report summarizes accomplishments towards implementing the NCSS over the last five years. A number of goals have been met, many are progressing, and others are in clear need of additional effort. Many of the recommended actions listed in the NCSS, particularly those expected to be addressed over the “medium-term”, are important to achieve as we continue to build towards a climate-ready NOAA Fisheries. Several in particular are highlighted below for priority consideration within each of three categories of the NCSS objectives:

Infrastructure and tracking change

- Rebuild ecosystem surveys to previous levels and expand where needed to fill in spatial and temporal gaps and account for anticipated shifts in species distributions
- Work with partners to leverage capacity and resources
- Produce regular updates of Ecosystem Status Reports in each region

[52] https://www.fisheries.noaa.gov/alaska/ecosystems/alaska-climate-integrated-modeling-project

- Ensure adequate resources are dedicated to climate-related research, process-oriented research (target a level of 10% of science budget)

Understanding mechanisms and projecting future conditions

- Identify regional data gaps and devise data collection and research programs to fill biological, physical, and socio-economic information needs
- Advance regional ocean and biogeochemical models
- Develop centralized databases and web tools to provide easy access to ecosystem and fisheries information, including species distribution shifts, ecosystem indicators, and stock status

Inform management

- Establish climate-smart terms of reference for incorporating climate and ecosystem information into management and policy areas (e.g. FMPs, FEPs, permitting, recovery plans, etc.)
- Work with fishery management councils to identify future climate and ecosystem scenarios (Scenario Planning) and evaluate risks and risk policies
- Operationalize MSE frameworks. This includes working with fishery management councils to identify their needs and identifying strategies robust to anticipated climate, ecosystem, and socio-economic conditions
- Present Ecosystem Status Reports to fishery management councils on an annual basis.
- Account for changing productivity and distribution for climate-smart BRPs

Clearly, meeting these goals will require enhanced and dedicated resources to support data collection and management efforts, IT infrastructure and modeling capacity, and fostering strong communication between scientists, managers, and stakeholders. Working together to support and address climate science and management needs will allow NOAA Fisheries to better meet its stewardship responsibility for the Nation’s living marine resources.

Table 9.1a. Progress on a selection of actions identified in the NCSS. Size and value of numbers indicate level of progress. 4 = completed; 3 = much; 2 = some; 1 = little.

Infrastructure and Tracking Change								
	NE	**Mid-Atl**	**South Atl**	**Gulf Mex**	**West Coast**	**Bering Sea**	**Gulf Ak**	**Pac. Isl.**
Establish/strengthen ESRs	4	4	1	3	4	4	4	3
Establish regional climate-LMR teams	4	4	4	4	4	4	4	4
Develop RAP	4	4	4	4	4	4	4	4
Initiate or expand partnerships	4	4	2	2	4	4	4	3
Bolster capacity to implement the NCSS	3	3	2	2	3	3	3	3
Ensure adequate resources dedicated to climate-related research	3	2	1	1	1	3	1	1
Increase awareness of and training on the impacts of climate change on LMRs	3	3	2	2	3	2	2	1

Table 9.1b. Progress on a selection of actions identified in the NCSS. Size and value of numbers indicate level of progress. 4 = completed; 3 = much; 2 = some; 1 = little.

Understand Mechanisms and Project Future Conditions								
	NE	**Mid-Atl**	**South Atl**	**Gulf Mex**	**West Coast**	**Bering Sea**	**Gulf Ak**	**Pac. Isl.**
Conduct Vulnerability Assessments	**4**	**4**	**3**	**3**	**4**	**4**	**1**	**3**
Strengthen production and delivery of output from climate-driven ROMs	**3**	**3**	**1**	**1**	**2**	**3**	**2**	**1**
Strengthen output from regional models for projecting climate impacts on LMRs in coastal and freshwater habitats	**2**	**3**	**1**	**1**	**3**	**2**	**2**	**2**
Identify and support process research linking changing climate and ocean conditions to LMR dynamics	**3**	**3**	**2**	**2**	**3**	**3**	**2**	**2**
Organize and conduct regime-shift detection workshops for each region.	**1**	**1**	**1**	**1**	**4**	**1**	**1**	**1**

Table 9.1c. Progress on a selection of actions identified in the NCSS. Size and value of numbers indicate level of progress. 4 = completed; 3 = much; 2 = some; 1 = little.

Inform Management								
	NE	**Mid-Atl**	**South Atl**	**Gulf Mex**	**West Coast**	**Bering Sea**	**Gulf Ak**	**Pac. Isl.**
Develop capacity to conduct MSEs	**3**	**3**	**2**	**2**	**3**	**3**	**2**	**2**
Establish climate smart ToRs to apply to LMR management requirements	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Evaluate risk policies under changing climate and ocean conditions	**1**	**3**	**1**	**1**	**1**	**2**	**1**	**1**
Conduct MSEs for climate scenarios in extant ecosystem and population models	**1**	**1**	**1**	**1**	**3**	**3**	**2**	**1**
Establish and implement standards and guidelines for incorporating climate into FMPs and FEPs	**1**	**1**	**1**	**1**	**1**	**3**	**1**	**2**
Establish science-based approaches for shifting BRPs to account for changing conditions	NA	NA	NA	NA	NA	NA	NA	NA

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