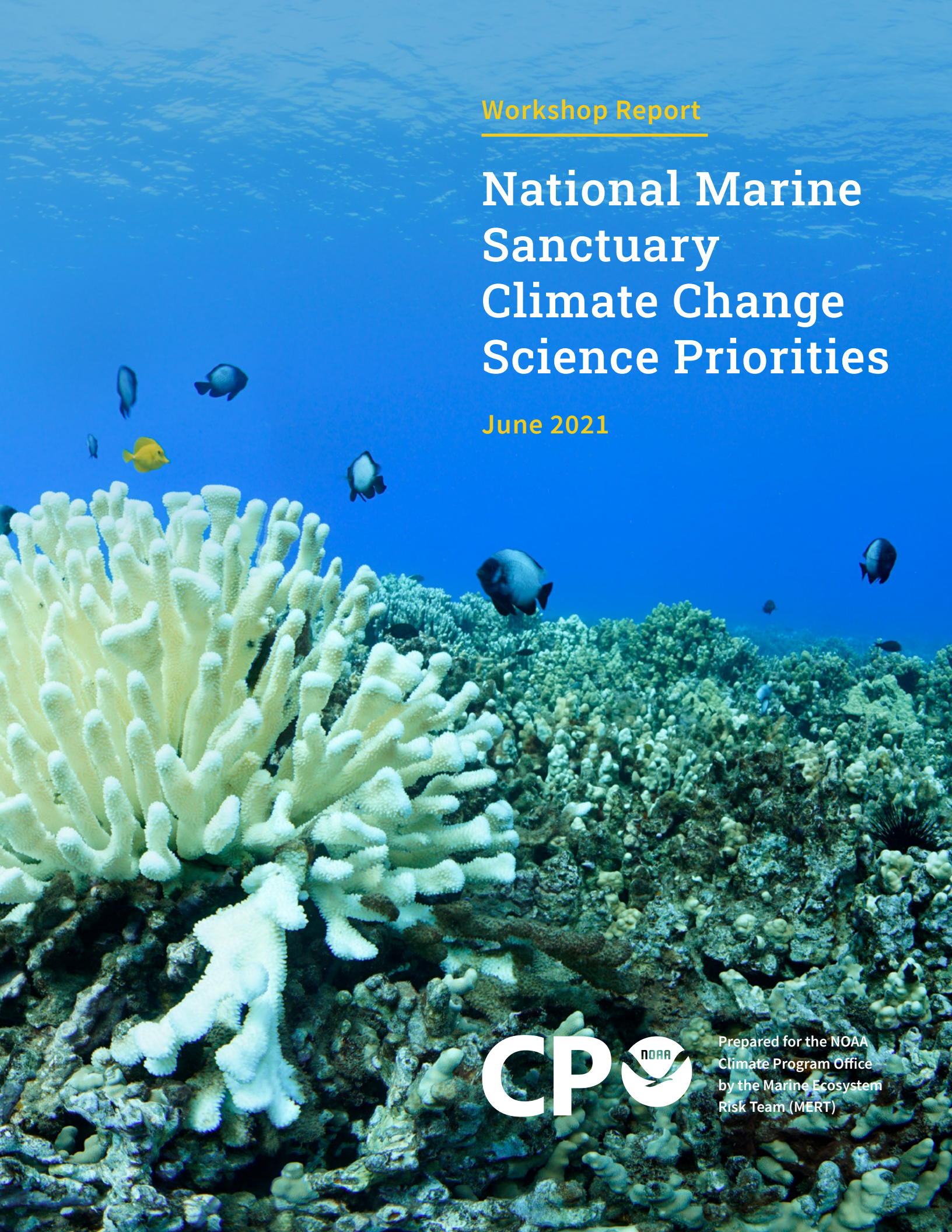

Workshop Report

National Marine Sanctuary Climate Change Science Priorities

June 2021

Prepared for the NOAA Climate Program Office by the Marine Ecosystem Risk Team (MERT)

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Cover photo: A bleached coral in Hawaiian Islands Humpback Whale National Marine Sanctuary. Photo: NOAA

Table of Contents

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Coral reefs in the National Marine Sanctuary of American Samoa and other sites in the National Marine Sanctuary System are one of the many important ecosystems being affected by the impacts of climate change. Credit: NOAA/NMFS/PIFSC/CRED, Oceanography Team

Section 1

Executive Summary

BACKGROUND

NOAA's Office of National Marine Sanctuaries (ONMS) and NOAA's Climate Program Office (CPO) Marine Ecosystem Risk Team (MERT) are partnering to advance Climate Science for Sanctuaries, an element of CPO's Climate Risk Area Initiative. MERT aims to advance climate research and modeling to reinforce and expand the application of climate science in national marine sanctuaries activities, and ultimately improve long-term planning and management of the National Marine Sanctuary System (NMSS) in support of NOAA's Stewardship mission. A major step in achieving this ambitious goal is to assess the current climate science and information needs of the NMSS. Towards this end, MERT and ONMS held the Sanctuaries Climate Priorities Workshop (workshop). Planning was led by MERT and a 12-member steering committee with representatives from NOS— ONMS (each site and headquarters), U.S. Integrated Ocean Observing System (IOOS), and National Centers for Coastal Ocean Science (NCCOS); OAR— Atlantic Oceanographic and Meteorological Laboratory (AOML), Geophysical Fluid Dynamics Laboratory (GFDL), Great Lakes Environmental Research Laboratory (GLERL), Pacific Marine Environmental Laboratory (PMEL), Physical Sciences Laboratory (PSL), Climate Program Office (CPO), Ocean Acidification Program (OAP), Sea Grant; NMFS—Southwest Fisheries Science Center; and NESDIS—the NOAA CoastWatch/OceanWatch/PolarWatch Program (hereafter, "CoastWatch").

The virtual workshop was held on January 26–28, 2021 and brought together over 130 participants.

The virtual workshop was held on January 26–28, 2021 and brought together over 130 participants from every site in the NMSS, representatives from

several programs in NOS, OAR, NMFS, NESDIS, and external organizations *(See Appendix D, Participant List*). The workshop provided an overview of the NMSS management and science process, highlighted ONMS-NOAA current climate research collaborations, and convened 38 topical breakout discussion groups (6–14 participants/group, facilitated by 1–2 chairs) to discuss potential ways to meet climate science and information needs previously identified through internal regional discussions held with ONMS in 2020. The identified climate science and information needs were:

Variability and change in physical processes relevant to marine ecosystems:

- Variability and change in subsurface ocean conditions
- Variability and change in land–sea dynamics
- Variability and change in regional- to local-scale physical oceanographic processes
- Extremes and large-scale climate phenomena

Impacts to species, ecosystems, and the services that depend on them:

- Ecological tipping points and thresholds in a changing ocean
- Ecological connectivity in a changing ocean
- Shifting species distributions and ecosystems
- Effects of changing ecologies on ecosystem services

Impacts to cultural and maritime heritage resources:

- Cultural resources in a changing ocean
- Maritime heritage resources in a changing ocean

Indicators and approaches to monitor and understand variability, change, and impacts:

- Development of climate indicators
- Interdisciplinary and applied data and integrated information needs

Breakout groups discussed these topics and their Issues, Capabilities, and Suggested Actions from the point of view of the full NMSS, and at the scale of the three ONMS regions (East Coast and Great Lakes, West Coast, and Pacific Islands). A plenary session was held at the end of each day to discuss major themes and important take-aways that arose from the breakout group discussions. After the workshop, the chair(s) developed summaries (*Appendix C*) of each breakout group.

This workshop report synthesizes the outcomes of the breakout group discussions and highlights the major needs and recommendations identified in the workshop. The report will help inform ONMS and the larger NOAA community on ways to advance and improve the climate-smart assessment, adaptation, and management of sanctuaries in support of NOAA's stewardship mission.

MAJOR NEEDS IDENTIFIED

The number and diversity of needs identified by workshop participants highlighted the lack of information that sanctuaries have when planning for current and future climate scenarios. While many of the identified needs were very specific to the individual sanctuaries, regions, or topics being discussed (*Appendix C*), those that cross-cut multiple breakout group topics are listed below (**see Section 3** for detailed discussion and additional context).

Data, Information, and Tools

- Incorporate multiple disciplines and perspectives into science, resource assessment and management, including traditional knowledge, maritime heritage, and socioeconomic questions
- Provide useful and usable data and tools
- Standardize protocols and data management to support dataset development and data sharing among sanctuaries and NOAA partners

Physical–Biological Coupling

- Improve understanding of physical–biological linkages and related ecological changes, particularly the impacts of extreme events and multiple interacting factors, to inform ecological forecast development

Observations and Monitoring

- Expand and enhance sanctuaries as climate sentinel sites
- Enhance coverage of physical and biogeochemical monitoring infrastructure within and across sanctuaries, particularly for subsurface conditions
- Determine ecological connectivity

Modeling Applications

- Expand existing modeling and prediction infrastructure to provide hindcasts, predictions, and forecasts on time and spatial scales meaningful to sanctuaries

Partnerships and Capacity

- Provide fora to integrate across the science–management interface
- Train ONMS staff on climate science and data
- Increase human capacity within ONMS to assess and address climate impacts

RECOMMENDED ACTIONS

Workshop participants identified a large number of actions that could be taken in the short-term (1–2 years), mid-term (2–5 years), and long-term (5–10 years). All of the recommended actions can be found in the breakout group summaries (*Appendix C*). Recommended cross-cutting actions are those that were identified in multiple breakout group topics for multiple regions and are listed below (**see Section 4** for detailed discussion and additional context).

Short-Term Actions (1–2 years)

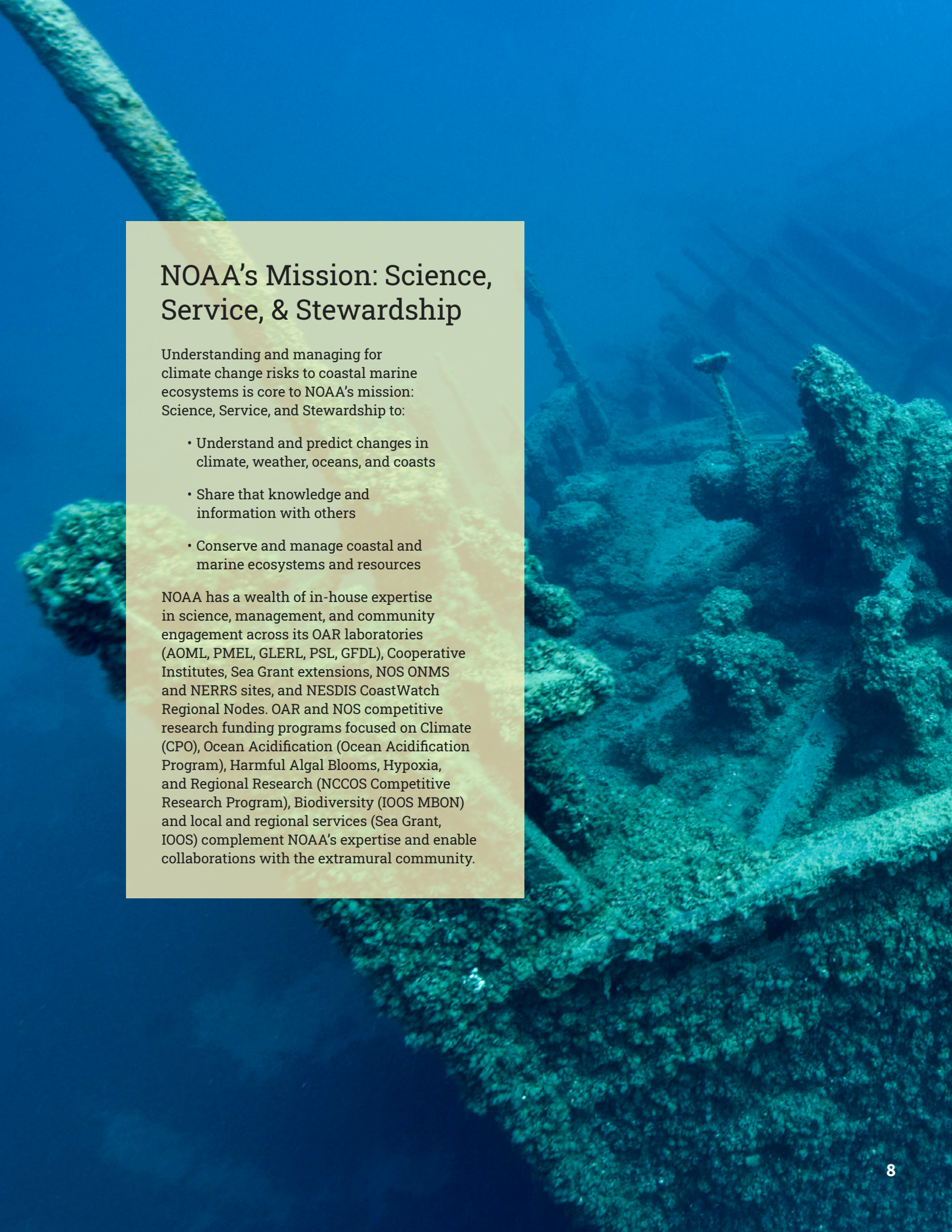
- ONMS should inventory climate-relevant scientific and outreach activities, datasets, and tools that exist throughout the NMSS and create an accessible repository of these resources
- Each site in the NMSS should work with NOAA partners to identify climate observational and research gaps
- ONMS headquarters should standardize climate indicators, reporting, and data management procedures across the NMSS
- Develop ecosystem service indicators and opportunities to advance socio-economic information relevant to sanctuaries and the communities they serve
- Integrate sanctuaries in the implementation of the NOAA Climate Fisheries Initiative
- Advance understanding of climate change effects on maritime heritage and cultural resources
- Assess the feasibility for ONMS to increase staff capacity in sanctuaries with expertise to support climate assessment and adaptation

Mid-Term Actions (2–5 years)

- Establish sanctuaries as formal and informal climate sentinel sites
- Develop and expand research initiatives that focus on advancing NOAA's ocean and climate monitoring and modeling capabilities
- Develop and expand research initiatives that improve the understanding of physical–biological linkages and the effects of multiple interacting stressors on living resources
- Develop and expand research initiatives that improve our understanding of ecological connectivity between marine sanctuaries and areas outside of them.

Long-Term Actions (5–10 years)

- Use climate information to inform the designation and expansion of sanctuaries, with a focus on protecting areas contributing to climate resilience
- Develop partnerships and tools to understand, anticipate, and manage the impacts of ecological tipping points with the potential to have high impacts on sanctuary ecosystems and local communities
- Improve and expand observing infrastructure within and across sanctuaries
- Build a collaborative network that allows for rapid responses to extreme events □

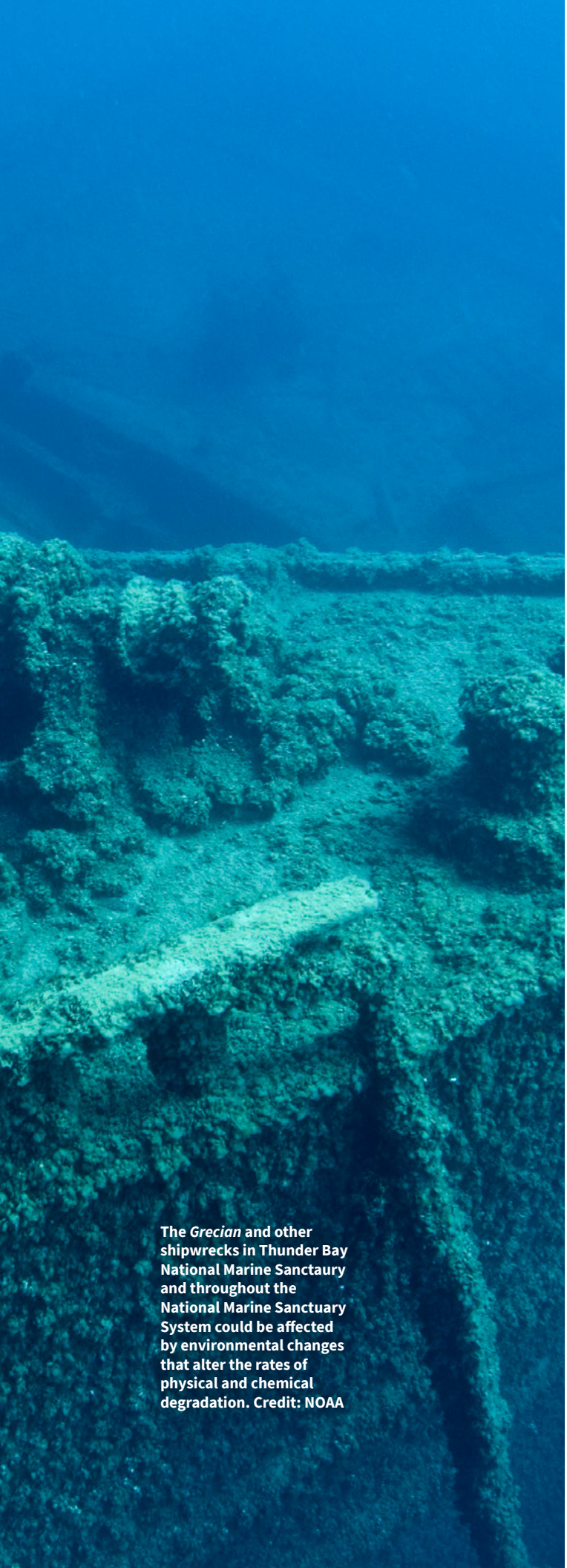


NOAA's Mission: Science, Service, & Stewardship

Understanding and managing for climate change risks to coastal marine ecosystems is core to NOAA's mission: Science, Service, and Stewardship to:

- Understand and predict changes in climate, weather, oceans, and coasts
- Share that knowledge and information with others
- Conserve and manage coastal and marine ecosystems and resources

NOAA has a wealth of in-house expertise in science, management, and community engagement across its OAR laboratories (AOML, PMEL, GLERL, PSL, GFDL), Cooperative Institutes, Sea Grant extensions, NOS ONMS and NERRS sites, and NESDIS CoastWatch Regional Nodes. OAR and NOS competitive research funding programs focused on Climate (CPO), Ocean Acidification (Ocean Acidification Program), Harmful Algal Blooms, Hypoxia, and Regional Research (NCCOS Competitive Research Program), Biodiversity (IOOS MBON) and local and regional services (Sea Grant, IOOS) complement NOAA's expertise and enable collaborations with the extramural community.



The *Grecian* and other shipwrecks in Thunder Bay National Marine Sanctaury and throughout the National Marine Sanctuary System could be affected by environmental changes that alter the rates of physical and chemical degradation. Credit: NOAA

Section 2

BACKGROUND

NOAA Mission & Capabilities in Support of Managing for Climate Impacts in the NMSS

NOAA has a wealth of in-house expertise in science, management, and community engagement across its OAR laboratories (AOML, PMEL, GLERL, PSL, GFDL), Cooperative Institutes, Sea Grant extensions, NOS ONMS and NERRS sites, and NESDIS CoastWatch Regional Nodes. OAR and NOS competitive research funding programs focused on Climate (CPO), Ocean Acidification (Ocean Acidification Program), Harmful Algal Blooms, Hypoxia, and Regional Research (NCCOS Competitive Research Program), Biodiversity (IOOS MBON) and local and regional services (Sea Grant, IOOS) complement NOAA's expertise and enable collaborations with the extramural community.

MANAGEMENT

The National Marine Sanctuaries Act (NMSA) authorizes NOAA to designate and protect areas of the marine environment with special significance due to their conservation, recreational, ecological, historical, scientific, cultural, archaeological, educational, or esthetic qualities... and oversee

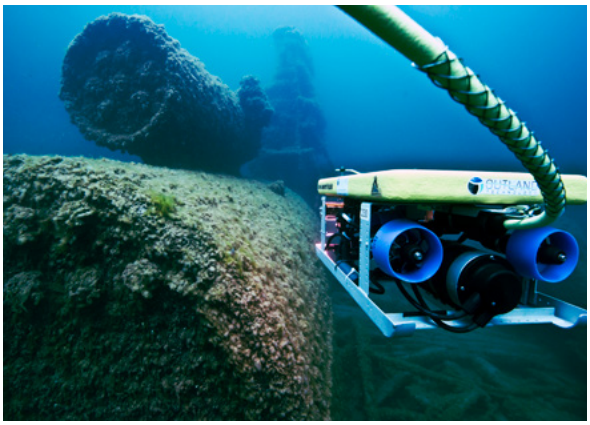
Map of the National Marine Sanctuary System including proposed national marine sanctuaries. Credit: NOAA

day-to-day management of the system. The National Marine Sanctuary System (NMSS) is composed of 14 national marine sanctuaries and two marine national monuments (all are hereafter referred to as "sanctuaries"). Managed by NOAA's Office of National Marine Sanctuaries (ONMS), the NMSS stretches from the Gulf of Maine to American Samoa and the Florida Keys to the Great Lakes (*see map above*). NOAA ONMS sanctuary superintendents and Headquarters are tasked with research, monitoring, and management of national marine sanctuaries. The NMSS has recently started incorporating climate impacts into Condition Reports, which assess sanctuary conditions at 10-year intervals. Some sanctuaries have also completed climate vulnerability assessments to further understand how climate threatens sanctuary resources; however, gaps in understanding remain. These reports inform current and future Science Needs Assessments and Sanctuary Management Plans, which set sanctuary management priorities and impact budgetary considerations (e.g., habitat restoration planning). Sanctuaries also play an important advisory role in working with other local, state, and Federal regulatory partners who have broader regulation and management authorities. In order to fulfill their mandates and work with regulatory partners, sanctuaries rely on NOAA's observing and modeling capabilities, and NOAA's collaborations with external partners.

NOAA has cutting edge observing technologies and expansive coastal observing infrastructure.

OBSERVATIONS

NOAA has cutting edge observing technologies and expansive coastal observing infrastructure. Participants highlighted OAR labs, NOS–IOOS Regional Associations (RA), IOOS Marine Biodiversity Observations Network (MBON), the National Coral Reef Monitoring Program (NCRMP), and sanctuaries and NERRS sites as entities that collect key coastal and ocean observations to meet NOAA's marine resource management/ stewardship mission areas. Additionally, OAR's



Remotely operated vehicles (ROV) and other cutting-edge NOAA technology allow sanctuary managers to observe and track changes in resources. Credit: Tane Casserley/NOAA

Ocean Acidification Program (OAP) research and observations have advanced NOAA's ability to understand and monitor ocean acidification impacts on marine resources, and NESDIS's CoastWatch provides fit-for-purpose satellite data products, tools and services for global ocean and coastal applications. Examples of observation-based information served by these programs range from social science, including human use patterns and community vulnerabilities, to real-time data generated by autonomous platforms and moored arrays, to eDNA analysis. NOAA's coastal observing is complemented by its global in situ observing presence, led by the Global Ocean Monitoring and Observing program.

MODELING

NOAA has an expanding coastal and regional ocean model enterprise with NOS and OAR participation that has applications in real-time, short-term, and long to distant-term at regional, and possibly sanctuary scales. On shorter timescales, IOOS-operated regional ocean models provide critical information for applications, such as harmful algal bloom monitoring (e.g. WCOFS-NEMURO, JSCOPE). On longer timescales, efforts are underway to perform regional downscaling of global climate models for ecosystem-relevant concerns with strong OAR lab involvement across regions. Model datasets such as CMIP6 data are available and have been used successfully to examine thresholds for some ecosystems (e.g., corals). Other model datasets, such as the recently developed Multimodel Large Ensemble Archive also allow for examining marine extremes.

INTEGRATION AND VISUALIZATION

Labs, regional associations, programs, and protected areas are not only pursuing research, but are collaborating with NOAA and external partners to integrate and deliver data from multiple sources to support an ecosystem approach to understanding and managing U.S. living marine resources. To support data dissemination, many groups use/serve data on the NOAA Environmental Research Division's Data Access Program (ERDDAP), an essential resource that makes data accessible for both visualization and download. Additional data integration and distribution examples include:

- Integrated Ecosystem Assessments or IEAs (National Marine Ecosystem Status)
- CoastWatch (CoastWatch)
- Coral Reef Watch (Coral Reef Watch)
- National Coral Reef Monitoring Program (NCRMP) (Coral Reef Monitoring)
- U.S. Integrated Ocean Observing System (IOOS Data Portals)
- Sea Grant (e.g., socioeconomic activities)

Other groups are also developing visualization tools. For example, OAR Physical Sciences Laboratory (PSL) has developed a web-based tool to compare reanalyses and display observational and model data (portal, comparison tool).

With NOAA's coastal observation and modeling system, complemented by a suite of subject matter experts in social, physical, and biological sciences, groups can work across the agency to advance the assessment and management of climate change and its impacts in sanctuaries. □

Better understanding changes to subsurface condtions and benthic communities in Gray's Reef National Marine Sanctuary and other sites in the National Marine Sanctuary System was identified by workshop participants as one of 11 priority cross-cutting needs. Credit: Greg McFall/NOAA

Section 3

Identified Cross-Cutting Needs

The number and diversity of needs identified by workshop participants highlighted the lack of information that sanctuaries have when planning for current and future climate scenarios. Needs are inclusive of gaps in understanding and information, modeling capabilities, tools, and products, as well as obstacles to accessing/using the former. A subset of needs cross-cut multiple breakout group topics and regions. Focusing on this subset would significantly advance the NMSS's ability to make informed management decisions and benefit the many site- and region-specific needs that are further detailed in the breakout group summaries (Appendix C). These cross-cutting needs often build upon each other and are identified and explored below under five broad topical areas.

The incorporation of the viewpoints of local communities, traditional knowledge, and other diverse perspectives into sanctuary managment will ensure more robust, equitable climate change assessment and management. Credit: Isabel Gaoteote/NOAA

3.1 Data, Information, and Tools

3.1.1 Incorporate multiple disciplines and perspectives into science, resource assessment, and management, including traditional knowledge, maritime heritage, and socioeconomic questions

Sanctuaries have built and maintained strong partnerships with local communities. Social science, cultural considerations, and economics are integral to condition reports and much of the other work sanctuaries conduct. Through partnerships with Sea Grant and other NOAA programs, climate considerations could be more fully integrated into these efforts. Participants recommended that ONMS climate assessment and management actions intentionally and purposefully incorporate more social science. This improved integration would lead to better management outcomes and community relationships. Breakout groups overwhelmingly highlighted the need to increase the incorporation of traditional knowledge into NOAA's climate science and place-based resource assessment and management.

Traditional knowledge and management practices have often been developed and employed successfully over thousands of years. These approaches can benefit sanctuaries by aiding in understanding past, present, and future changes, particularly where reliable long-term datasets are not available, and in identifying and improving understanding of culturally important resources at each NMS site. Traditional knowledge is currently an underutilized resource for NOAA science and management, and its broader understanding

Social science, cultural considerations, and economics are integral to condition reports and much of the other work sanctuaries conduct.

and use depends upon the development of long-term, respectful relationships with Indigenous communities. There is also a general lack of information pertaining to the impacts of climate change on the maritime heritage and cultural resources that are important to local communities and stakeholders, and more research and understanding of these impacts is needed to fully achieve NOAA's stewardship mission. The improved incorporation of these multiple disciplines and perspectives into resource assessment and management will create a more holistic and robust climate assessment and management process.

3.1.2 Provide useful and usable data and tools

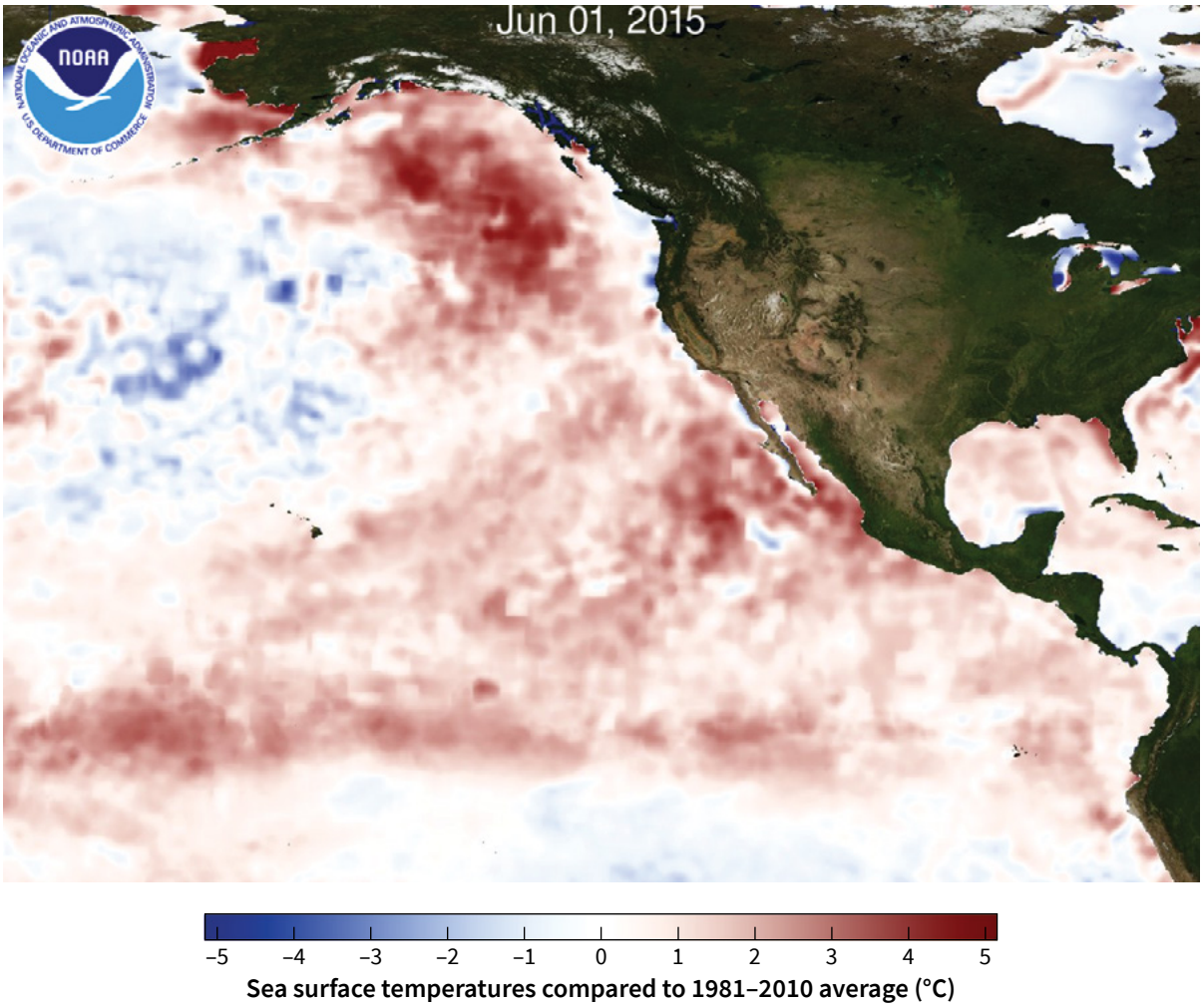
The need for useful and usable climate information, data, and tools was consistently identified. Sanctuaries require access to data and tools on meaningful spatial and temporal scales to successfully assess and manage for climate impacts. For example, a sanctuary concerned with future sea level rise requires accurate sea level projections that resolve coastal features relevant to management, such as small inlets, and at seasonal to decadal timescales in order to make informed management decisions.

Participants highlighted that existing data and modeling capabilities can already answer in full or in part many sanctuary climate data and information needs. However, existing data and tools also need to be usable. To be usable, these data and tools must be findable, and helpful to sanctuary managers and staff, who may have limited capacity to use or interpret complex scientific tools and data, such as model output. To address the gap between data availability and usability, more effort and support is required to distill models and data into digestible formats and easy-to-use tools. Examples of successful tools already exist in the form of Coral Reef Watch and the "webenized" (hosted on an accessible and interactive web page) indicators developed for sanctuaries in partnership with the IEA program. Improving findability and usability through the development of additional tools, such as data portals and dashboards, will require increased communication and collaboration between NOAA data producers and sanctuary managers to ensure information is portrayed in an accurate but understandable format. Participants suggested a workshop or matchmaking exercise between NOAA programs may also be helpful in this context.

3.1.3 Standardize protocols and data management to support dataset development and data sharing among sanctuaries and NOAA partners

Lack of standardization and consistency across the NMSS is a major barrier to addressing climate information and management needs. NOAA and sanctuary partners noted the NMSS data and information gaps are unclear: what is missing versus what already exists? Participants suggested ONMS: 1) standardize sampling procedures, data management, and reporting across NMSS, and 2) inventory existing climate-relevant datasets, tools, and scientific and outreach activities, including data collected in sanctuaries by others, and capture these in a centralized, accessible repository (e.g., data hub or portal) accessible via ERDDAP. Beyond ONMS data management efforts, there is a need for a NOAA-wide centralized clearing house or data hub of climate-relevant observational and modeling data. Such a data hub should contain all appropriate climate-relevant data generated and owned by NOAA staff in accordance with federal data management standards. This NOAA-level portal should be designed and maintained to facilitate access and usability for a range of scientific and technical expertise to maximize its usefulness.

These data efforts would provide foundational support for the development of a common set of ONMS climate variables and indicators. Participants recommended that indicators be prioritized that could be applied system-wide, but still provide relevant information at the regional and sanctuary scales. Efforts would also enable data sharing across the NMSS, increase the use of NMSS data to parameterize models, and aid in the identification of data and information gaps. Providing scientists with increased access to NMSS data will allow for products that are more accurate and precise, improving their applicability and usefulness to sanctuaries. The development of common protocols and standardization of datasets across the NMSS and its primary partners will accelerate and increase the success of partnerships and sanctuary climate management.



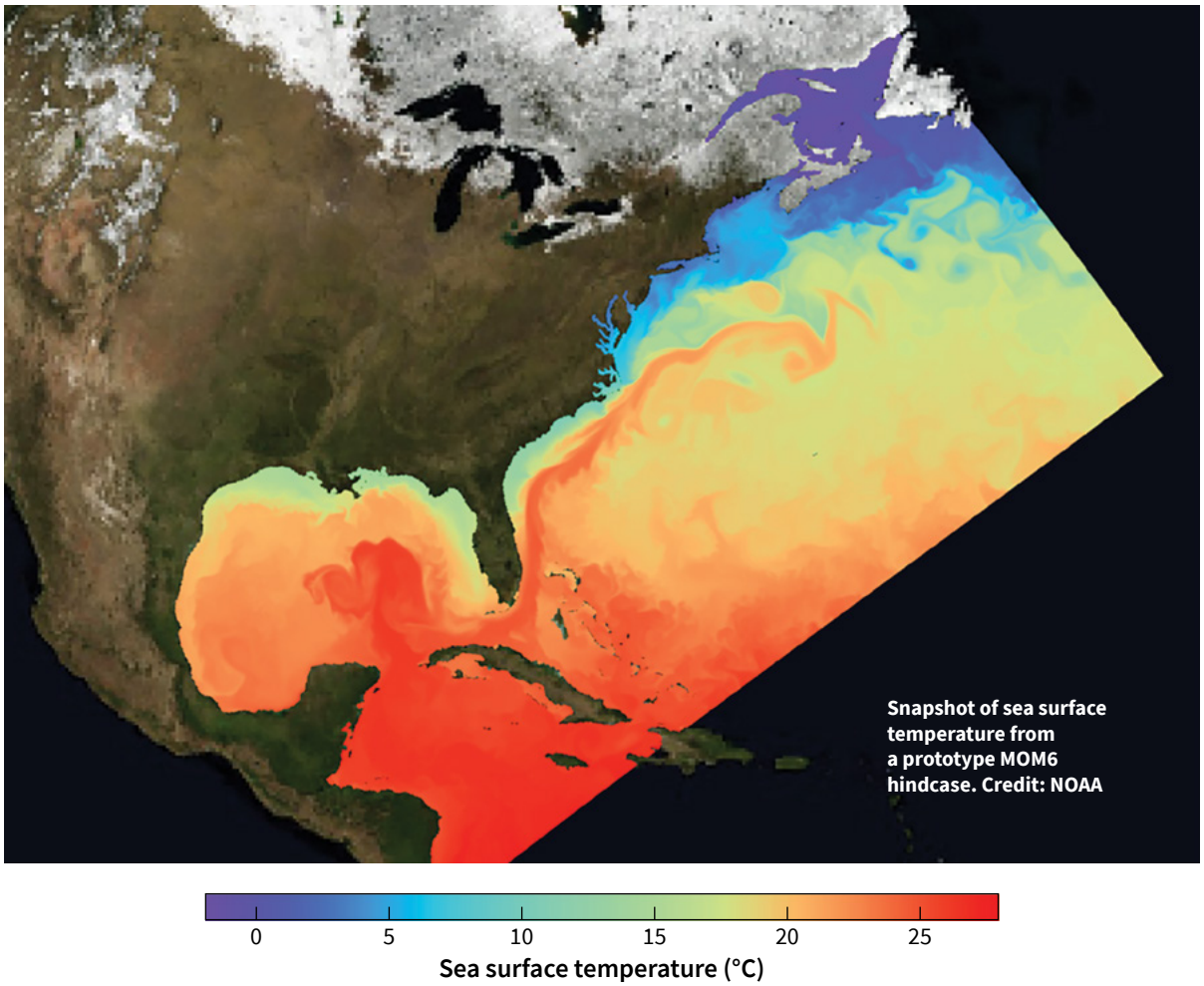
This image shows the effect of the Pacific Ocean marine heat wave known as the Blob on sea surface temperatures on June 1, 2015. Credit: NOAA

3.2 Physical–Biological Coupling

3.2.1 Improve understanding of physical–biological linkages and related ecological changes, particularly the impacts of extreme events and multiple interacting factors, to inform ecological forecast development

Given the prevalence and importance of ecological resources to sanctuaries, stakeholders, and local communities, increasing the ability to understand and predict how these resources will respond to future conditions was a focus of numerous breakout groups. Thus, a major scientific need identified by workshop participants was improved understanding and modeling of the linkages between physical (including biogeochemical) factors and biological parameters to better understand and predict ecological changes. Improving the understanding of these linkages, and NOAA's ability to successfully model their consequences, is a key component in addressing a number of the topics discussed by breakout groups.

Sanctuary managers in particular highlighted both the need for improved understanding of how extreme events and multiple-stressor interactions impact living resources and the need to communicate this information in an actionable way. Across several breakout groups, participants noted that most projections of how living resources will respond to changing conditions only examine single stressors when, in reality, organisms are being exposed to multiple stressors. The ultimate response of organisms and ecosystems to changing



Snapshot of sea surface temperature from a prototype MOM6 hindcase. Credit: NOAA

conditions will result from the interaction of these multiple simultaneous stressors. Understanding how ecosystems respond to extremes (such as hurricanes or marine heatwaves) and multiple stressors is a clear gap that must be bridged in order to apply models to marine ecosystem management applications. Participants also highlighted that short-term warning systems are needed to inform sanctuary managers of impending climate events (such as extreme events) with ecological consequences. NOAA's Coral Reef Watch was highlighted as a gold standard for such warning systems and the development of a "Kelp Watch" and other similar warning systems were commonly identified needs that will greatly improve the ability of sanctuaries to make informed management decisions. The development of these forecasts depends on improved model linkages between physical and biological factors.

Advancing foundational understanding of physical–biological linkages related to ecosystem impacts, translating these into ecological modeling advancements, and developing easy to use, understandable forecasts of ecological phenomenon such as species range shifts and ecological tipping points will help sanctuary managers make informed and decisive management decisions ranging from identification of sanctuary boundaries to prioritization of resources for restoration and protection. Improvements in these areas will greatly advance the ability of sanctuary managers to support NOAA's stewardship mission with informed management decisions and timely and accurate information for the public. Sanctuaries are in a unique position to collaborate with partners in addressing these needs as they will act as both users of the information and critical test beds to collect observations and validate model output.

3.3 Observations and Monitoring

3.3.1 Expand and enhance sanctuaries as climate sentinel sites

Sanctuaries are public-facing locations that have built trusted relationships with local communities and stakeholders. Visitor centers, webinars, and face-to-face interactions with visitors make sanctuaries important fora to communicate science and management. Further, as permanently protected places under the management of the federal government, sanctuaries are valuable locations for climate-relevant research and the collection of invaluable long-term datasets. Thus, sanctuary sites not only provide platforms for long-term monitoring of climate and ecological variables, but also communicate observed change and impacts to local communities. NOAA has the opportunity to expand and enhance the role of sanctuaries as climate sentinel sites, informally or through ONMS's internal sentinel site program, where reliable, standardized, long-term datasets that are central to actionable climate science can be developed. This will meet the growing need of ONMS to determine climate impacts and identify and protect refugia, as well as the demand of the scientific community for reliable long-term data and observations to validate and constrain models.

3.3.2 Enhance coverage of physical and biogeochemical monitoring infrastructure within and across sanctuaries, particularly for subsurface conditions

While the role of sanctuaries as climate sentinels was highlighted, participants noted that in order for sanctuaries to reach their full potential, monitoring infrastructure within and across sanctuaries needs to be expanded. As permanent, federally managed places, sanctuaries represent ideal locations for long term observations such as buoys and monitoring stations. Satellite-based observations can complement in situ observations for surface environmental conditions. Yet, sufficient infrastructure and data integration across platforms within and across sanctuaries is lacking. Participants recognized that increasing these capabilities across the NMSS will provide the high-quality, long term datasets and real-time data needed to parameterize and validate modeling, monitoring, and forecasting tools at the management-relevant scales that sanctuaries need.

In particular, participants emphasized the need for increased biogeochemical observations throughout the water column including the seafloor. While most existing monitoring and observational infrastructure focuses on the surface, many sanctuaries protect benthic and pelagic resources that would be better served by an increased understanding and ability to predict changing physical and biogeochemical conditions throughout the water column. Addressing these gaps will require increased long-term investment in in situ data collection throughout the water column and on the seafloor. Sanctuaries will need to work with partners, such as the National Data Buoy Center (NDBC) and IOOS RAs who are experienced in the deployment, maintenance, and operation of observational infrastructure. Addressing observation-limited areas for sanctuary applications will require a sustained capacity and financial investment from both sanctuaries and partners. Data produced from these efforts are vital to improving and validating models at the cutting edge of NOAA's Earth Systems prediction capabilities and will provide sanctuaries with the valuable information they need to make informed management decisions.

3.3.3 Determine ecological connectivity

Workshop participants across multiple breakout groups and regions identified a need for better tools and methodologies to understand and measure ecological connectivity. Specifically, there is a need for increased capacity to understand how individual sanctuary sites within a region are physically and biologically connected to each other and large-scale land–sea and ocean dynamics. This includes consideration of the movement of populations, individual organisms, genes, gametes, and propagules between populations, communities, and ecosystems; impacts of ocean circulation on local and regional sanctuary scales; the transport of freshwater, nutrients, and pollutants at the land–sea interface; and other biogeochemical factors that affect sanctuary water quality and resources. Meeting this need will require enhanced observational and modeling capabilities, as well

as the use of innovative tools. The opportunity to leverage advances in 'omics and environmental DNA (eDNA) technologies and methodologies was noted extensively by workshop participants while existing telemetry and observational networks were also highlighted as valuable. Addressing these gaps will allow sanctuaries to better make decisions related to site management, designation, and expansion in a changing ocean and will require a diverse set of partners within and outside of NOAA.

3.4 Modeling Applications

3.4.1 Expand existing modeling and prediction infrastructure to provide hindcasts, predictions, and forecasts on time and spatial scales meaningful to sanctuaries

The need to expand modeling and prediction infrastructure on temporal and spatial scales meaningful to sanctuaries was one of the most commonly expressed needs across breakout groups. Participants noted improved hindcasts, predictions, and forecasts for coastal areas and the subsurface; linkages between ocean models and dynamic terrestrial models; and improved skill in biogeochemistry, upwelling, near surface circulation, and internal wave dynamics are needed to improve the ability of managers to understand changes occurring in sanctuaries and make informed management decisions.

Improved forecasts and projections of benthic and subsurface predictions throughout the water column will prove particularly useful as many sanctuaries manage resources that are mostly or exclusively found in the water column and/or on the seafloor. Further, participants emphasized the need for products, such as forecasts (as discussed in the Physical–Biological Linkages **Section 3.2**) that provide early warning to sanctuary managers of impending extreme events. Development of these forecasts will require improved understanding of and ability to model the impacts of and triggers/mechanisms behind extreme events and large-scale climate phenomena such as hurricanes, harmful algal blooms, hypoxic events, El Niño Southern Oscillation (ENSO), and marine heatwaves.

Advancing regional models and configurations was noted as a required approach to addressing the larger modeling needs of sanctuaries described in the previous paragraphs. Participants noted that a comparison between in situ sanctuary data with NOAA's climate models will help assess the relevance and skill of these models and forecast tools, determine where observational gaps exist, and improve model skill. In this way, sanctuaries represent both users of model information and partners by providing the data to parameterize, constrain, and test modeling capabilities.

3.5 Partnerships and Capacity

3.5.1 Provide fora to integrate across the science–management interface

Participants found the workshop and similar fora valuable and suggested NOAA provide more opportunities to integrate across the science–management interface within NOAA, and with external partners. Tools and capabilities to meet the climate needs of sanctuaries already exist within NOAA and fora such as this workshop and the NOAA Climate Connections event (2019) are critical to increase user awareness of these capabilities and help scientists and developers understand how they will be used and where adjustments are needed. Additional matchmaking exercises or workshops to connect sanctuary needs with NOAA climate capabilities and providers was a common suggestion. This would be especially valuable in building a list of identified experts to contact for specific event response, sampling needs, and advice when events arise. Workshops and roundtables focused on specific topics were also identified as some of the most efficient and effective strategies to finding solutions and accelerating progress. These fora enable discussions that spark the intra-NOAA partnerships necessary to meet not only the climate management challenges faced by

sanctuaries, but those of the nation. Ultimately, breaking down the science and management silos that are pervasive within NOAA through fora that bring scientists and managers together will greatly accelerate NOAA's ability to provide solutions to the climate management challenges faced by both sanctuaries and the nation.

3.5.2 Train ONMS staff on climate science and data

Participants noted that while there is a need for NOAA scientists and programs to create data and tools that are usable to sanctuary staff (**Section 3.1.2**), there is also a need to increase the knowledge base of sanctuary staff, managers, and scientists. This includes promoting and facilitating training on how to use and interpret model datasets and their associated uncertainties, and providing formal training in products and tools, such as those provided by CoastWatch to facilitate the exploitation of satellite data in applications. Additionally, a formal program such as a climate science certification within sanctuaries was suggested as a strategy to help address the limited climate capacity of ONMS staff and scientists. Such training and communication will increase the capacity of existing sanctuary scientists and staff to assess and implement climate science in order to develop and advance management priorities.

3.5.3 Increase human capacity within ONMS to assess and address climate impacts

Even with increased training, participants noted that staff have finite capacity and that additional staff positions will be necessary to fully assess and address climate impacts. Many sanctuary climate needs can be met through partnerships, but participants noted that the most efficient and sustained climate assessment and adaptation requires the institutional knowledge and relationships that can only be achieved by staff embedded within the sanctuary system. While sanctuaries currently have staff with extensive scientific and management expertise, staff often do not have additional capacity to devote to climate change issues, and expertise on individual subjects, such as climate change, is not evenly distributed among sites and regions. Suggestions for how to meet this need ranged from having dedicated climate scientists and modelers at each site to creating dedicated climate coordination positions at the regional and headquarters levels. Additionally, participants noted that some of this additional capacity can be met through fellowship and postdoctoral positions, while other gaps will require the creation of new staff positions. Nevertheless, to meet the management challenges presented by a changing ocean, ONMS must increase its staff capacity to assess and address climate change and its impacts on sanctuaries, while considering budget constraints and balancing future priorities. □

Fellowships and scholarships, such as the Dr. Nancy Foster Scholarship Program, are one way in which sanctuaries can increase human capacity to address climate impacts. Credit: Julie Chase/ACCESS/NOAA Point Blue Conservation Science

Working with partners to train staff and increase human capacity are some of the most effective ways to increase the ability of sanctuaries enhance their assessment and management of climate change impacts. Credit: NOAA

Kelp forests in Monterey Bay National Marine Sanctuary and other sanctuaries on the West Coast are experiencing changing conditions that can alter ecological function. Credit: Jon Anderson, NOAA ONMS

Section 4

SUGGESTED STRATEGIES

How to Advance Climate Science in Sanctuaries

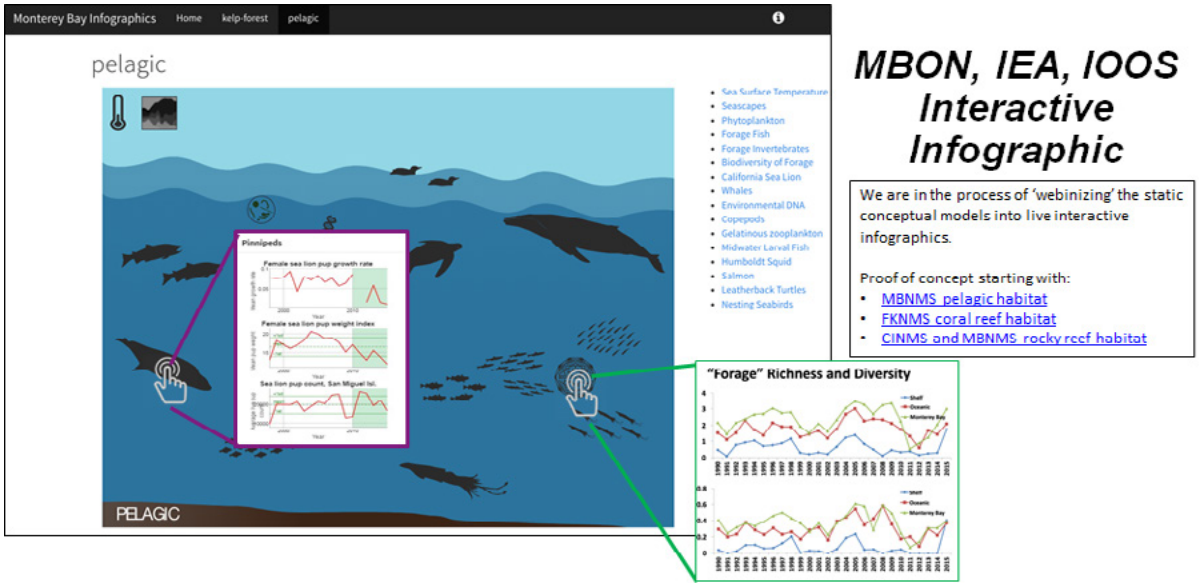
Workshop participants identified a large and diverse set of actions that could be taken in the short-term (1–2 years), mid-term (2–5 years), and long-term (5–10 years) to address the identified needs and topics of discussion. These represented a broad range of fields from basic science and management considerations to data management and partnership development. The capacity to complete these actions ranges from the time of a single staff member to multi-agency partnerships. Resource managers, scientists, or program managers interested in actions related to a specific breakout topic or sanctuary region can review the comprehensive list found among the breakout summaries (Appendix C). Recommended cross-cutting actions identified in multiple breakout groups and across regional scales are summarized below. Participants identified these as actions that could address, or allow for substantial progress towards addressing, needs discussed in Section 3. The order in which these actions are listed does not signify a perceived order of importance. A table identifying the needs (Section 3) supported by each action can be found at the end of this section.

Kelp forests in Sanctuaries on the West Coast are critical ecosystems for many marine organisms. Credit: Chad King/NOAA

4.1 Short-Term Actions (1–2 years)

The actions described below are those that participants identified where rapid progress can be made. These actions are often those where NOAA capabilities exist to meet ONMS needs, or where ONMS can make substantial progress without technical aid (although additional capacity may be necessary).

4.1.1 ONMS should inventory climate-relevant scientific and outreach activities, datasets, and tools that exist throughout the NMSS and create an accessible repository of these resources. An early step in understanding what climate information sanctuaries need from partners is for sanctuaries to make an account of the climate datasets, activities, and tools that already exist throughout the system (**Need 3.1.3**). This includes both data produced and owned by the sanctuaries, but also data and activities that were undertaken by partners within or in partnership with sanctuaries. While this action will need to be coordinated and led by ONMS headquarters, it will require participation from every site in the NMSS. Compiling this information into an easily accessible repository will allow sanctuary managers and scientists to better understand the status and trends of relevant environmental variables at individual sites and throughout the system. These data would also allow for increased collaboration between sites and facilitate the development of standardized indicators (**Action 4.1.3**). To be most successful, this will require system-wide standardization of data management and procedures (**Need 3.1.3**). Further, the compilation will aid the identification of data gaps where the incorporation of traditional knowledge could be particularly valuable (**Need 3.1.1**). When made accessible to partners, the repository will



NOAA IEA and National Marine Sanctuaries are working in partnership with the US Integrated Ocean Observing System program (IOOS) and the US Marine Biodiversity Observing Network (MBON) to develop dynamic infographics from the static habitat conceptual models (i.e. webenizing conceptual models). Credit: NOAA IEA, MBON, IOOS

also provide valuable data that can be used to parameterize models and forecasts to make them more accurate and scalable to sanctuaries (**Need 3.4.1**). From a practical standpoint, the creation of this ONMS repository will facilitate partnerships with NOAA scientists and increase ONMS climate capacity (**Need 3.5**) by directly contributing to data sharing and integration into centralized repositories (**Need 3.1.3**). The repository developed from these data must be useful and usable to sanctuary managers and partners (**Need 3.1.2**). It should be designed to allow for easy querying and visualization of the data, such as in the model of the "webenized" condition report indicators designed in partnership with the IEA program, to increase its utility. A multipronged approach to developing the repository was suggested:

- Each site in the NMSS should produce a summary of the climate data at their site, compile these data electronically, and prepare them for archiving in a centralized repository. Given the decentralized nature of the NMSS, each site will need to first inventory and compile their climate-relevant scientific activities, datasets, tools, and outreach activities, including those produced and owned by partners. While it will vary on a site-to-site basis, the research coordinator will often lead this effort and compile the datasets in formats that can be transferred to a centralized repository.
- ONMS headquarters should develop and maintain a centralized repository of ONMS climate-relevant data independently or with a NOAA partner. Once the climate-relevant data are compiled across the NMSS, they will need to be organized and archived in a centralized and accessible repository. ONMS could develop and maintain its own such repository but it will be more efficient to leverage existing NOAA tools, such as ERDDAP, to organize and archive these data. Archiving the data into a partner data repository, such as NEDIS' National Centers for Environmental Information (NCEI) would further allow it to be accessible to managers and scientists throughout the NMSS and NOAA.

4.1.2 Each site in the NMSS should work with NOAA partners to identify climate observational and research gaps.

Participants noted that an early and important step for NOAA partners to help sanctuaries meet their climate needs is for sanctuaries to provide a simple accounting of what those needs are. While this report and associated products (*see Appendix C*) serve as a type of system-wide inventory of needs, and primes regional and

site-specific conversations, each site and region should summarize its own climate information and capacity needs, and then work with NOAA partners to determine what can be addressed with existing capabilities, highlight gaps, and highlight sanctuary specific priorities. An inventory of existing climate-relevant information (**Action 4.1.1**) and observation infrastructure in each sanctuary is a first step in completing this action. This would not only provide the information that partners need to develop useful and usable information and tools for sanctuaries (**Need 3.1.2**), but would also allow sanctuaries to explore areas where additional observational infrastructure within the NMSS may be most useful (**Need 3.3**). Sanctuaries are currently in the process of developing science needs assessments to communicate their science needs to partners and the public. A climate needs assessment that also includes identified observational capacity, and other climate-related needs is a logical offshoot of this initiative.

4.1.3 ONMS Headquarters should standardize climate indicators, reporting, and data management procedures across the NMSS.
Workshop participants noted a need for sanctuaries to develop standardized sampling procedures, data management, and reporting across the NMSS for climate indicators and for climate-relevant data more generally (**Need 3.1.3**). Standardizing reporting and data management across the NMSS is necessary to allow for meaningful comparisons and evaluations of status and trends between sites and across the NMSS. It will also allow partners to more easily integrate data across sites and the system to create the useful and usable products sanctuaries require (**Need 3.1.2**) and create models and forecasts that are more spatially and temporally meaningful to sanctuaries (**Need 3.4.1**) and their resources (**Need 3.2.1**). Such standardization will also facilitate the archiving and sharing of data both within ONMS and with NOAA partners (**Need 3.1.3**). The creation of a set of standardized climate indicators for the NMSS and each region will also allow the consistent tracking of changes across the system necessary for informed management and will help establish sanctuaries as climate sentinel sites, either informally or through ONMS's internal sentinel site program (**Need 3.3.1**). The collection of standardized data related to these indicators would provide the high-quality, long-term datasets needed to parameterize the models and forecasts that sanctuaries and the nation need to make informed management decisions in a changing ocean (**Needs 3.2.1, 3.4.1**). While this report presents a preliminary list of recommended sanctuary climate indicators produced by workshop participants (**see Section 5**), more work is necessary to develop a definitive set of standardized indicators that are trackable and not overly numerous or onerous. MERT and the workshop committee recognize that it may not be possible to achieve the full scope of this recommended action in the 1–2 year timeframe prescribed. However, it has been placed in the short-term category because it is possible for ONMS and its partners to make significant progress with the information, tools, and capacity that already exist. For instance, in the near term, participants suggested that a logical and powerful way to both develop a robust set of climate indicators for the NMSS and continue to integrate across the science–management interface (**Need 3.5.1**) is to hold a workshop to identify a set of climate indicators for the NMSS.

4.1.4 Develop ecosystem service indicators and opportunities to advance socio-economic information relevant to sanctuaries and the communities they serve.
The ecosystem services that sanctuary resources provide to visitors, stakeholders, and coastal communities will be altered by climate change. To successfully track, anticipate, and mitigate negative impacts to these changes, sanctuaries will need to identify indicators that enable tracking of these services (**Need 3.1.1**). The action favored by workshop participants was either an indicators development workshop (similar to or as a part of that proposed in **Action 4.1.3**) or the development of a funding opportunity by a NOAA partner like CPO or Sea Grant for the identification of regional ecosystem services indicators and the promotion of novel approaches to integrating varying datasets on human use and human dimensions in relation to climate factors.

4.1.5 Integrate sanctuaries in the implementation of the NOAA Climate Fisheries Initiative.
The Climate Fisheries Initiative (CFI) is an extensive cross-line office partnership between OAR and NMFS to enhance NOAA's climate modeling and

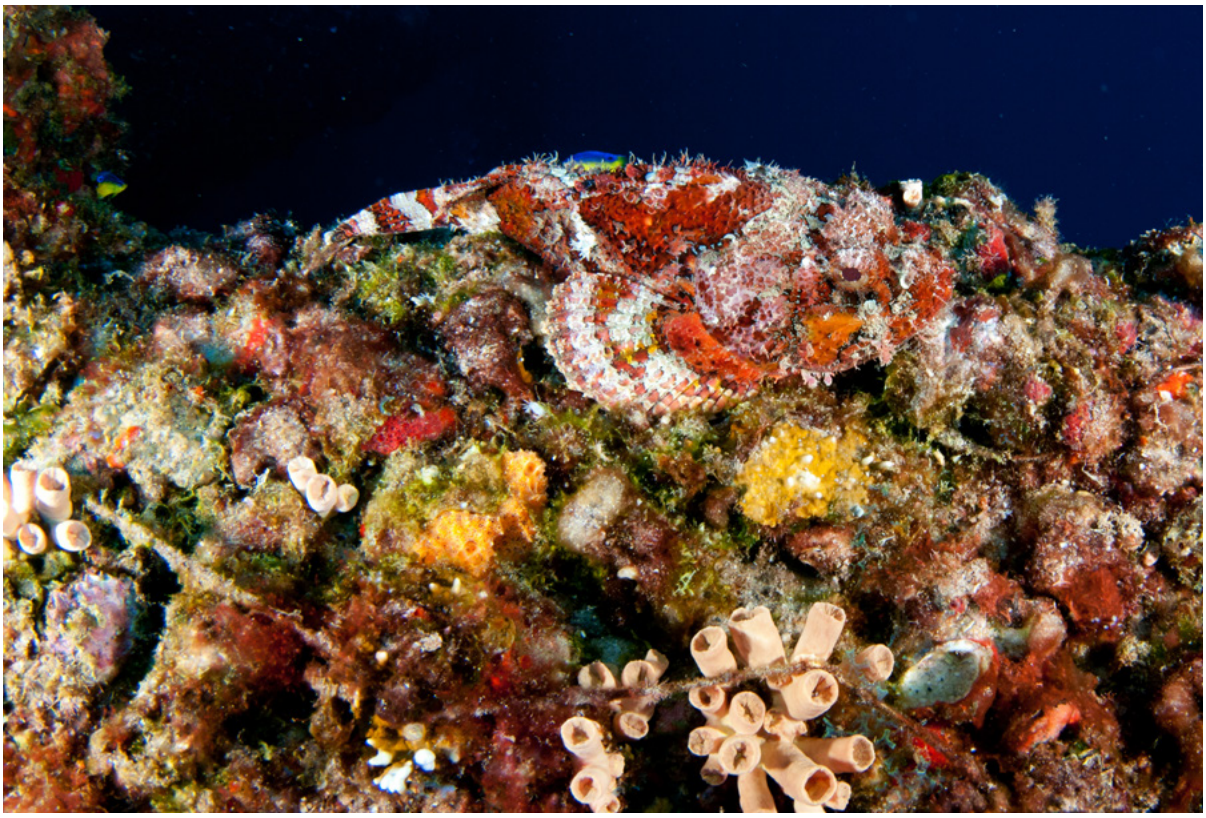
Understanding the impacts of climate change on maritime heritage resources, such as the USS *Tarpon* in Monitor National Marine Sanctuary, was identified by workshop participants as a priority short-term action. Credit: Tane Casserley/NOAA

forecasting capabilities with a focus on ecological resources. While the initiative was developed around the needs of NMFS, many of the proposed products and outcomes are of direct relevance to sanctuaries and would greatly contribute to meeting numerous needs identified by workshop participants (**Needs 3.2.1, 3.4.1**). More fully incorporating sanctuaries into the implementation of the CFI as a stakeholder will ensure that the products developed through the initiative are useful and usable to resource managers (**Need. 3.1.2**). Sanctuaries also have a role to play as partners in the CFI as locations where data can be collected to parameterize, constrain, and test the models and forecasts being produced (**Need 3.2.1**).

4.1.6 Advance understanding of climate change effects on maritime heritage and cultural resources .
Workshop participants noted that despite the importance of maritime heritage and cultural resources to the mission of sanctuaries, there is relatively little understanding of the impacts of climate change on these resources (**Need 3.1.1**). Thus, participants suggested that NOAA find ways to fund research initiatives focused on these impacts. As stewards to many of our nation's unique and important maritime heritage resources, sanctuaries protect resources and places that are culturally significant to a range of communities. While this work will take years to complete, this was identified as a near-term action because work must begin immediately to fill this critical scientific gap and meet NOAA's stewardship mission.

Participants noted a first step is for sanctuaries and partners to identify and catalog the cultural resources (living, place-based, and intangible) found at each site in the NMSS (**Need 3.1.1**). As climate change will impact these resources, it is important to know what resources exist, where they are located, and who finds them important. As cultural resources are often a focus of traditional knowledge that is of use to sanctuary climate management, gaining a better understanding of the cultural species and resources found in each site will aid sanctuaries in the incorporation of traditional knowledge into their science and management (**Need 3.1.1**).

4.1.7 Assess the feasibility for ONMS to increase staff capacity in sanctuaries with expertise to support climate assessment and adaptation.
The need for increased human capacity with the skills and knowledge to advance and maintain sanctuary climate assessment and adaptation within ONMS was identified in numerous breakout groups (**Need 3.5.3**). Given limited funding and the time it takes to move through hiring processes, ONMS could begin immediately to examine how, where, and when to strategically increase human capacity. Participants noted that some additional capacity can be met through fellowship and postdoctoral positions internally and with partners, but other gaps will require the creation of new staff positions.



Improved understanding of the physcial–biological linkages would improve the ability of managers at Flower Garden Banks National Marine Sanctuary and other sites in the National Marine Sanctuary System to understand and predict changes to benthic and other ecological communities. Credit: G.P. Schmahl/NOAA

4.2 Mid-Term Actions (2–5 years)

The actions described below are those that participants identified where significant progress will require time to develop, but can be made within a few years. These actions are often those where NOAA capabilities exist but will require additional development to meet ONMS needs, require outside support, and/or require significant investment. ONMS and its partners could begin these actions soon. While these actions are attainable in the mid-term, they will require extensive collaboration, planning, and/or investment.

4.2.1 Establish sanctuaries as formal and informal climate sentinel sites.
As permanent, place-based protected areas, sanctuaries can meet the growing needs for observations of changes to the environment and ecological community (**Need 3.3**), the identification of refugia, and the production of the long-term, high quality datasets necessary to parameterize advanced climate and ecological models and forecasts (**Needs 3.2.1, 3.4.1**).

Sanctuaries can leverage their capability to act as both data users and data producers informally or through the formal designation of ONMS sentinel sites. The enhancement and expansion of the ONMS sentinel site program, with a focus on sites that can act as sentinels for climate-relevant parameters (e.g., Olympic Coast Ocean Acidification Sentinel Site), could be a focus of sanctuaries (**Need 3.3.1**). Achieving this action will require sanctuaries to expand and develop

NOAA and external partnerships and work across the science–management interface (**Need 3.5.1**).

Depending on the focus of the sentinel sites, achieving this action may require the expansion and development of new observation and monitoring infrastructure (**Need 3.3.2, 3.3.3**), facilities, or scientific capabilities; enhanced climate science training of staff (**Need 3.5.2**); and/or new human capacity within ONMS or through partnerships (**Need 3.5.3**). The time, effort, and financial investment required to meet this action is significant, but it would represent a significant achievement, elevate ONMS as a leader in climate assessment and management, lead to enhanced NOAA climate data products, and help meet a number of the needs identified in this workshop. This action should not fall to ONMS alone, but rather leverage other NOAA investments to fill the gap between current sanctuary resources, and those needed to achieve this action. The establishment of a network of climate sentinel sites within sanctuaries would provide an integrated long-term monitoring network to support both ocean climate research and management needs, elevating both sanctuaries and other NOAA programs. ONMS could immediately begin the process of exploring where and how to expand the system of sanctuary climate sentinel sites through internal means and through NOAA and external partnerships and funding.

4.2.2 Develop and expand research initiatives that focus on advancing NOAA's ocean and climate monitoring and modeling capabilities

The ability to project and forecast changes to physical and biogeochemical surface and subsurface conditions at temporal and spatial scales meaningful to sanctuaries is of great importance to ONMS and the resources they protect (**Needs 3.2.1, 3.4.1**). However, NOAA's ability to successfully monitor and model subsurface conditions lags behind that of the surface. Given this gap, workshop participants recommended that NOAA programs increase their focus on funding and enhancing subsurface modeling capabilities. While some downscaling and regional modeling capabilities and products already exist through IOOS, OAR, and NMFS, participants suggested that NOAA focus on developing improved regional downscaling of CMIP6 and other models. As place-based, federally-managed protected areas, sanctuaries will be important partners in providing data and case studies to modeling efforts. These actions will also be an important step towards improving subsurface physical and biogeochemical modeling capabilities (**Needs 3.2.1, 3.4.1**), and would help fill a critical gap in global ocean and ecological modeling and forecasting capabilities. Improving the regional-scale outputs of these models would be a step toward addressing needs ranging from meaningful forecasts of ecological impacts (**Need 3.2.1**) and extreme events (**Need 3.4.1**) to an increased ability to link ocean and terrestrial models (**Need 3.4.1**).

...there is a pressing need to expand the understanding and ability to link physical, chemical, and biological factors to understand, project, and forecast ecological changes.

4.2.3 Develop and expand research initiatives that improve the understanding of physical–biological linkages and the effects of multiple interacting stressors on living resources

Many of the workshop breakout groups discussed the effects of climate change on the living resources and ecosystems that sanctuaries protect. Workshop participants noted that there is a pressing need to expand the understanding and ability to link physical, chemical, and biological factors to understand, project, and forecast ecological changes (**Need 3.2.1**). Participants also recognized that living resources and ecosystems are experiencing multiple climate and nonclimate stressors simultaneously and, therefore, there is a need for improved understanding and modeling of the responses of living resources and ecosystems to multiple stressors (**Need 3.2.1**). To meet these needs, NOAA could develop initiatives to improve the understanding of physical–biological linkages, including the effects of interacting stressors, and fund both the applied science and model development to address these gaps in understanding. Existing initiatives such as MBON and the Climate Fisheries Initiative (CFI) have the technical expertise and vision to begin to achieve this action. NOAA must continue to fund these and

other relevant initiatives and research including the development of modeling capabilities that link physical, biogeochemical, and biological processes to understand and project future ecological changes. In addition, sanctuaries could continue and expand their engagement in initiatives and working groups such as MBON and CFI (**Action 4.1.5**) to ensure that the research funded and products developed are useful and usable to sanctuaries (**Need 3.1.2**). Sanctuaries can also play a role in completing this action by providing areas to conduct this research, data to parametrize models, and partnerships to develop meaningful questions. Ultimately, the data and products produced by such initiatives will aid the ability of sanctuary and other resource managers (e.g., fisheries) to make informed management decisions for the ecological resources under their protection, many of which are of great importance to coastal communities and stakeholders (**Need 3.1.1**).

4.2.4 Develop and expand research initiatives that improve our understanding of ecological connectivity both between marine sanctuaries and to areas outside of them

The ability to detect, monitor, and project how sanctuaries are connected to both each other and other areas by regional and basin-scale ecological and physical processes (termed ecological connectivity) is important to sanctuaries (**Needs 3.3.3, 3.4.1**) and other NOAA and non-NOAA stakeholders. Projects and partnerships such as MBON and the Animal Telemetry Network focus on biological connectivity, largely through animal movement, across scales and could be expanded and coupled with modeling efforts. Model improvements and better integration and coupling between land and coastal ocean modeling efforts are also needed to capture this interface. Enhanced observing capabilities to address connectivity questions (**Need 3.3.2, 3.3.3**) will support the representation of these processes in models (**Need 3.4.1**) and improve understanding of the response of living resources to discrete events (Need 3.4.1) and long-term change (**Need 3.2.1**). A focus on examining physical–biological coupling and processes at the land–sea interface at multiple scales will accelerate the development of the connectivity products and forecasts sanctuaries and other stakeholders, such as regional fishery management councils, need to make informed decisions related to future changes to resources.

A better understanding of the ecological connectivity between habitats such as mangroves (*top*) and coral reefs (*bottom*), and how these connections may be impacted by climate change, was identified as a priority mid-term action by workshop participants. Credit: (*top*) NOAA, (*bottom*) Tom Moore/NOAA

Change photo caption to read: Long-term actions will be critical to successfully manage the impacts of climate change at Cordell Bank National Marine Sanctuary and throughout the national marine sanctuary system. Credit: Joe Hoyt/NOAA

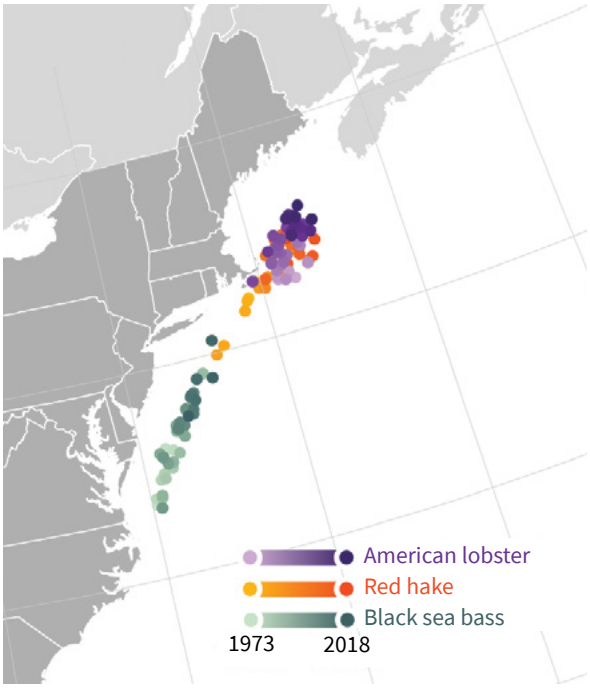
4.3 Long-Term Actions (5–10 years)

The actions described below are those that participants identified where significant progress will require time and sustained development over the coming decade. These actions are often those where new NOAA capabilities will need to be developed, or significant time and/or monetary investment will be necessary. ONMS, CPO, and partners could pursue the development of these actions as they will require extensive and sustained collaboration, planning, and/or investment over the coming decade but have high potential to provide long-lasting and impactful outcomes.

4.3.1 Use climate information to inform the designation and expansion of sanctuaries, with a focus on protecting areas contributing to climate resilience

In order for the NMSS to leverage its full climate management potential, workshop participants suggested that ONMS meaningfully and purposefully use climate information to inform the designation and expansion of sanctuaries. Workshop participants recognized that climate considerations cannot be the only factor in determining sanctuary designation and expansion, but noted that they should not be ignored. Climate information can be used to both determine if projected changes will make the mission of proposed sanctuaries unachievable (e.g., target species will shift out of proposed areas), to identify areas where sanctuary protection could have outsized benefits (e.g., blue carbon ecosystems, climate refugia, areas that may be important to key species shifting their distributions), and when protection of resources might require new models of designation and

management, such as dynamic management. While this is an action that ONMS can begin to take immediately, it will require the development of meaningful criteria as well as additional capacity and funding. Participants recognized that it will take time for these criteria to be implemented successfully (thus the placement of this action into the long-term category). ONMS should explore options for supporting an effort to formally incorporate climate considerations into sanctuary designation and expansion.



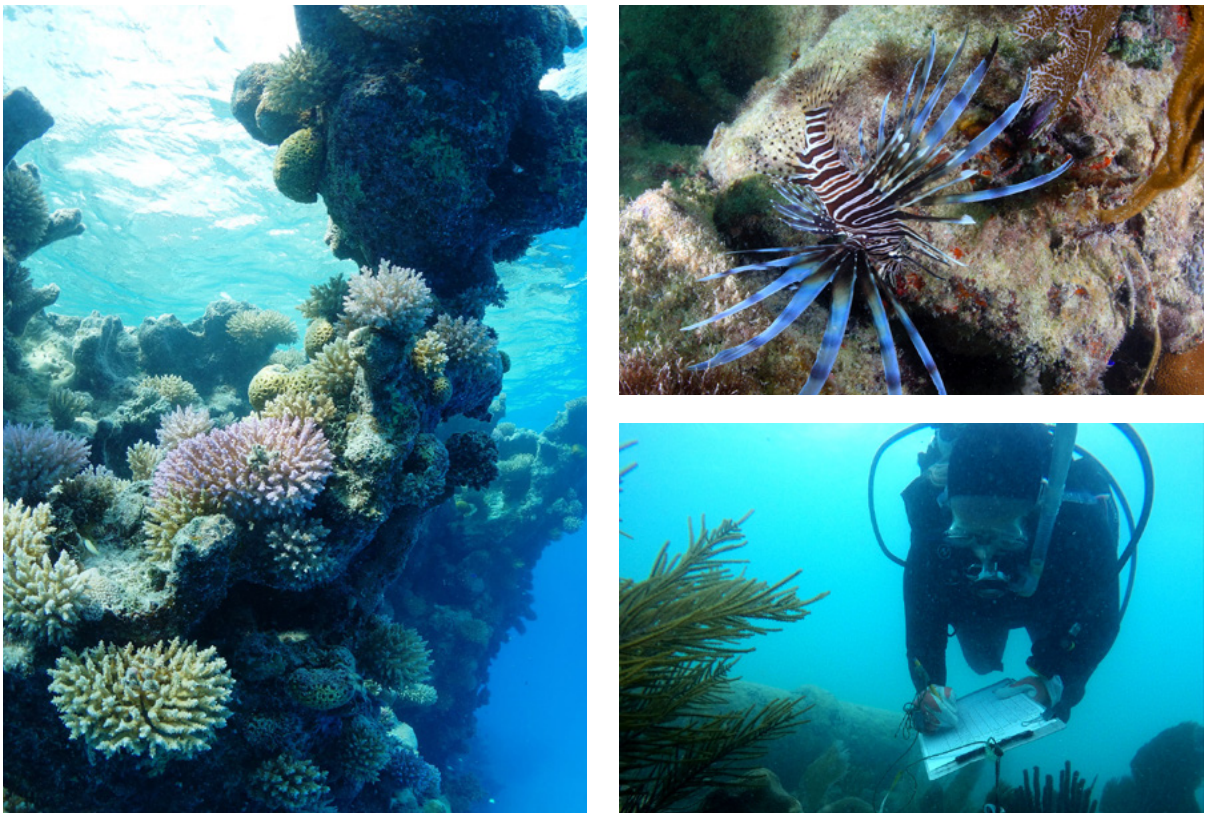
Northward shift in average location of American lobster, red hake, and black sea bass in the North Atlantic from 1973 to 2018. Credit: NOAA Climate.gov, adapted from USGCRP Climate Indicators.

4.3.2 Develop partnerships and tools to understand, anticipate, and manage the impacts of ecological tipping points with the potential to have high impacts on sanctuary ecosystems and local communities

The discussion of ecological tipping points garnered the most interest among the workshop participants of all the breakout topics. The topic of tipping points and thresholds even arose in the discussion of other topics, such as ecosystem services, due to the cascading and long-lasting impacts they can have on the resources sanctuaries protect, and the services they provide. There was also an understanding that while tipping points and thresholds need to be more clearly defined, they are a critical component of understanding the vulnerability of sanctuary resources to climate change and are likely to become more common in the future. Thus, participants suggested that NOAA pursue and develop partnerships and tools to understand, forecast, and manage ecological tipping points and thresholds. This will require a dedicated investment in the basic research needed to understand the triggers of these events and the biophysical modeling necessary to project and forecast not only their occurrence, but also their impacts (**Needs 3.2.1, 3.4.1**). Given that each ecosystem is unique in its potential tipping points and triggers, participants suggested that NOAA focus on those possible tipping points with the potential to have high impacts on ecosystems and the services they provide to coastal communities (**Need 3.1.1**). Participants suggested a priority-setting workshop to inform a focused research initiative (**Need 3.5.1**). Ultimately, participants suggested that sanctuaries and their partners should focus on the development of products that can track and forecast tipping points and their effects. NOAA's Coral Reef Watch was commonly held up as an example of such a product and the development of similar products for other ecosystems of importance to sanctuaries, such as a "Kelp Watch," was a commonly suggested action and would greatly aid sanctuaries in their ability to make informed management decisions (**Need 3.1.2, 3.2.1**). There are a number of NOAA programs, such as CoastWatch, NCRMP, and IOOS, that have the experience and tools needed to begin work on the production of tools to forecast these tipping points, and manage their impacts, where sufficient knowledge already exists (e.g., kelp; see the National Park Service's Resist-Adapt-Direct framework for an example of how others manage the impacts of tipping points and similar ecosystem changes). Thus, while this action will require sustained support and development in coming years, there are areas where rapid progress can and should be made.

4.3.3 Improve and expand observing infrastructure within and across sanctuaries

Workshop participants suggested that sanctuaries work with other NOAA programs to expand and enhance the network of observational and monitoring infrastructure that already exists within sanctuaries (**Needs 3.3.2, 3.3.3**). As permanent, federally-managed areas, sanctuaries



Addressing and understanding impacts such as bleaching coral (*left*), shifting and invasive species (*top right*), and changing environmental conditions will require improved observation (*bottom right*) and partnerships across the National Marine Sanctuary System. Credits (*clockwise from left*): Wendy Cover/NOAA, Greg McFall/NOAA, Brenda Altmeier/NOAA.

represent the ideal locations for the deployment of monitoring infrastructure such as buoys and monitoring stations. However, for sanctuaries to fully live up to their potential as climate sentinel sites (**Need 3.3.1**), the network of this observing infrastructure will need to be expanded both within individual sanctuaries and across the NMSS, and integrated with other NOAA observing assets. In particular, NOAA should prioritize observing infrastructure that would help to fill critical gaps in knowledge, such as subsurface physical and biogeochemical observations and monitoring of ecological and physical connectivity (**Needs 3.3.2, 3.3.3**). NOAA programs such as NDBC, OAP, CoastWatch, NCRMP, IOOS, and others should partner with ONMS to identify the location and type of observational infrastructure that is most needed to parameterize critical models and fill data gaps. While sanctuaries are critical partners in the deployment and maintenance of such infrastructure, they cannot be solely responsible for their upkeep without substantial increases in financial and human capacity. Thus, it will either be necessary for partners to commit to sustained funding and maintenance of new observational and monitoring capacity or for NOAA to significantly increase the funding and capacity available to ONMS for this endeavor. While this sustained investment is substantial, the benefits of a comprehensive observing network in combination with the resource management and science capabilities associated with sanctuaries will provide extensive benefits to the nation. Given the time and resources it will take to achieve this action, participants suggested that sanctuaries and their partners begin these discussions now through fora such as a working group or workshop (**Need 3.5.1**) in order to begin the time and resource intensive process of acquiring and deploying this infrastructure as soon as possible.

4.3.4 Build a collaborative network that allows for rapid responses to extreme events

Extreme events such as hurricanes, marine heatwaves, and hypoxic events can have sudden

and drastic consequences for sanctuary ecosystems, resources, and coastal communities. As a result, participants identified improved modeling and forecasting of these events as a critical need (**Need 3.4.1**). In response, participants suggested that sanctuaries and their partners tap into the NMSS' status as a permanent place-based system, and build collaborative networks to respond to these events when they occur. Given the often large scope of these events, the development of multiple interrelated networks corresponding on system-wide and regional levels is necessary. In addition to coordinating management responses to such events, these networks should take advantage of the opportunities they provide to gather data on event triggers and impacts. NOAA could develop these integrated networks and work towards supporting an optimized observational and modeling approach that would aid in rapid response to extreme events. The successful establishment of these networks and the outcomes of their work would provide benefits to sanctuaries and coastal communities as the nation continues to grapple with the increasing frequency and magnitude of extreme events. □

Table: Matrix of Identified Cross-Cutting Needs and Suggested Actions: "Phys–Bio" stands for "Physical–Biological Coupling, "Model" stands for "Modeling Applications". Blue shading indicates actions that support the corresponding need. White diamonds indicate complementary needs and actions where working towards one will advance the other.

SUGGESTED STRATEGIES		IDENTIFIED CROSS-CUTTING NEEDS										
		Data, Information, and Tools			Phys–Bio	Observations and Monitoring			Model	Partnerships and Capacity		
		3.1.1	3.1.2	3.1.3	3.2.1	3.3.1	3.3.2	3.3.3	3.4.1	3.5.1	3.5.2	3.5.3
Near-Term Actions	4.1.1	■	◆	■					■	■	■	■
	4.1.2		■			■	■	■				
	4.1.3		■	■	■	■			■	■		
	4.1.4	■										
	4.1.5		■		■				■			
	4.1.6	■										
	4.1.7											■
Mid-Term Actions	4.2.1				■	■	■	■	■	◆		◆
	4.2.2				■				■			
	4.2.3	■	◆		■							
	4.2.4				■		■	■	■			
Long-Term Actions	4.3.1											
	4.3.2	■	■		■				◆	◆		
	4.3.3						■	■		◆		
	4.3.4								■			

A robust, standardized set of climate indicators will allow sanctuaries to track environmental changes at Florida Keys National Marine Sanctuary and across the National Marine Sanctuary System. Photo: Greg McFall/NOAA

Section 5

Climate Indicators for Sanctuaries

A major objective for ONMS is to develop a common set of indicators to track and assess climate change and its impacts across the NMSS. Breakout group discussions on system-wide and regional indicators (East Coast/Great Lakes, West Coast) were supportive of existing, ongoing indicator discussions. While no breakout group discussion was held to discuss climate indicators for the Pacific Islands Region, determining such indicators will be important moving forward.

To date, sanctuaries use about 50 different indicators to determine status and trends as a part of their Condition Report Process (*Appendix C*). Workshop participants used this list as a starting point to identify the indicators that would be most useful for tracking climate change and its impacts in sanctuaries, while also identifying gaps and proposing new indicators. Indicators are currently collected primarily at the level of individual sanctuaries, but for impacts related to climate change, information is needed at regional and larger scales. System-wide assessments of climate impacts will require standardization of both collection protocols and data reporting (**Needs 3.1.3; Actions 4.1.1, 4.1.3**). NCEI was noted by participants as the gold standard for such standardization and a key partner in achieving this goal.

Participants also noted that sanctuaries have limited capacity to gather and process the data required to assess and track the expanded list of NMSS climate and related impact indicators. Enhanced NMSS

monitoring and observing infrastructure (**Needs 3.3.2, 3.3.3; Action 4.3.3**); tools to readily interpret indicator data, such as dashboards, time-series, and interactive graphics (**Need 3.1.2**); and the capacity to process data and improve data access/availability (**Needs 3.5.2, 3.5.3**) will all be necessary to achieve this goal. Increased capacity could be met through partnerships, fellowships, postdoctoral positions, and/or existing (through training) or new employees, but will require sustained funding by either ONMS or its partners. Partners such as NDBC, IOOS, MBON, OAP, NCRNP, and IEA, among others, will be key to ONMS implementing a full suite of climate indicators for the NMSS. These and other partners have the tools and expertise to aid in the development and tracking of indicators. Many have already developed their own indicator systems that ONMS could leverage for more complete analyses and assessments, particularly on regional and system-wide scales.

While this list of recommended climate indicators represents an output of the workshop, it should be noted that participants strongly suggested a full independent workshop to discuss and develop a definitive set of climate indicators for the NMSS and each region (**Need 3.1.3; Action 4.1.3**). **The list presented here should be considered input to inform ONMS ongoing indicator discussions and can be used as a starting point for a targeted workshop.** Participants also noted that it would be useful for the research coordinators at each sanctuary to determine if they are already collecting data on indicators of climate relevance as a part of a broader inventory of ONMS climate data (**Need 3.1.3; Action 4.1.1**). This could both help inform the development of an agreed-upon set of ONMS climate indicators and provide the data for initial assessments and gap analyses.

Ultimately, the development of a standardized set of climate indicators for the NMSS will allow sanctuaries to track changes in the qualities of water, habitats, living resources, heritage resources, and ecosystem services to make more informed management decisions in a changing ocean. Sanctuaries already track or use many climate-related (e.g., sea surface temperature) and nonclimate factors to assess conditions and some would be part of a comprehensive climate indicator set. Below is the list of suggested climate indicators grouped into the major topics of water quality, physical/oceanographic, biological, and social/ecosystem service indicators. These include system-wide recommended indicators, as well as those specific to the West Coast Region, and the East Coast and Great Lakes Region. As no breakout group was held to discuss indicators for the Pacific Islands Region, no recommended indicators are presented here.

Accurately tracking climate change in ecosystems such as coral reefs (*top*) and the organisms that depend on them (*bottom*) throughout the National Marine Sanctuary System requires a robust set of climate indicators. Credit: (*top*) Greg McFall/NOAA, (*bottom*) Steve Lonhart/NOAA

Hawaiian Islands Humpback Whale National Marine Sanctuary and other sites in the National Marine Sanctuary System can serve as important locations to evaluate environmental changes by tracking climate indicators with assistance from NOAA and non-NOAA partners. Credit: J. Moore/NOAA

5.1 System-Wide Climate Indicators

The indicators identified below are broadly applicable and could be gathered at every sanctuary to assess and track climate change and its impacts across the NMSS.

This list represents priority indicators as identified by workshop participants, but more work will be necessary to prioritize indicators, develop standardized sampling protocols, and standardize data management across the NMSS (**Need 3.1.3, Action 4.1.3**).

5.1.1 System-Wide Water Quality Climate Indicators

Workshop participants identified six water quality parameters as key to assessing and tracking climate change and its impacts across the NMSS. Many of these indicators are already assessed by sanctuaries as part of the Condition Report process. Each should be tracked at the surface and subsurface. Further discussion is required to determine standardized depth, depth intervals, or reference (i.e., "bottom") for subsurface measurements.

- Water Temperature
- pH
- Alkalinity
- pCO2
- Dissolved Oxygen
- Salinity

5.1.2 System-Wide Physical/ Oceanographic Climate Indicators

Workshop participants identified six physical/ oceanographic parameters that are key to assessing and tracking climate change and

its impacts across the NMSS. Many of these indicators will require sanctuaries to gather or assess additional data beyond those already examined during the Condition Report process. While some have been used in assessments with conditions reports, these are not currently broadly assessed either regionally or system-wide.

- Mixed Layer Depth/Stratification
- Sea Level
- Storm Frequency and Intensity
- Runoff
- Frequency of Significant Anomalies (e.g., Marine Heatwaves)
- Basin-Scale Drivers of Ocean Conditions (PDO, NPGO, NAO, ENSO, etc.)

5.1.3 System-Wide Biological Climate Indicators

Workshop participants identified eight biological parameters that are key to assessing and tracking climate change and its impacts across the NMSS. Many will require sanctuaries to gather or assess additional data beyond those already examined during the Condition Report process. Further, given the differing ecologies found across the NMSS, development of these indicators will require additional discussion to ensure that they are comparable across sites and regions.

- Keystone species indices: abundance, distribution, condition, recruitment rate; keystone species will need to be identified for each site/region.
- Frequency and intensity of harmful algal blooms
- Biological impacts of acidification: shell thickness, calcification rates, erosion rates (reefs, concretions, etc.); species or other resources to track these impacts will need to be identified for each site/region.
- Changes to phenology/timing of relevant biological events
- Recruitment rates for non-indigenous and invasive species
- Relative abundance, diversity, and composition of zooplankton—each site/region will need to determine which zooplankton species to track. Workshop participants suggested a number of candidates including pteropods, krill, and copepods such as Calanus finmarchicus.
- Genetic and species diversity obtained via eDNA—allows for tracking of presence/absence of species in the sanctuary or at a key location.
- Habitat compression—a derived metric that is a measure of habitat suitable for occupation and normal ecosystem function. This indicator is a reflection of changing conditions throughout the NMSS.

Leveraging partnerships and cutting-edge NOAA technology will be vital to the ability of sanctuaries to successfully develop and track climate indicators. Credit: NOAA

5.1.4 System-Wide Social/Ecosystem Service Climate Indicators

Workshop participants noted significant gaps in indicators currently used to assess climate impacts on coastal communities, human dimensions, and ecosystem services in sanctuary condition reports. They identified five social/ecosystem service indicators that are key to assessing and tracking climate change impacts to social and economic systems across the NMSS. They will require further development and represent a starting point for discussion.

- Number of fishers
- Catch rates for important fishery species
- Social Vulnerability Indicators
- Local Access to Seafood
- Opportunities to Practice Social Traditions

5.2 Regional Climate Indicators

In addition to the system-wide indicators identified above, workshop participants identified a number of indicators of particular importance to assessing and tracking climate change impacts in the West Coast Region and the and East Coast and Great Lakes Region.

These should be considered in addition to the system-wide indicators, not as a substitute. The diversity of ecosystems in the East Coast and Great Lakes region necessitate the use of generalized indicators. Participants identified a number of indicators that are of particular relevance to sanctuaries in the Great Lakes. Similar to the system-wide indicators, more work will be needed to prioritize regional indicators, develop standardized sampling protocols, and standardize data management across sites within and across regions (**Need 3.1.3, Action 4.1.3**). As no breakout group was held to discuss indicators for the Pacific Islands Region, no recommended indicators are presented here but determining such indicators should be a focus in the future.

Tracking sea level rise and coastal impacts of climate change at Greater Farallones National Marine Sanctuary and throughout the National Marine Sanctuary System will help sanctuary managers better understand the impacts of climate change. Photo Credit: Matt McIntosh/NOAA

5.2.1 East Coast and Great Lakes Region Water Quality Climate Indicators

- Nutrient Concentrations: Nitrogen, Phosphorous, Silicate

5.2.2 East Coast and Great Lakes Region Physical/Oceanographic Climate Indicators

- Wave Intensity and Frequency
- Wind Speed and Direction
- Sound Diversity and Intensity
- Regional Changes in Precipitation
- Changes to Current Direction and Speed

5.2.3 East Coast and Great Lakes Region Biological Climate Indicators

- Coral Recruitment (two sanctuaries)
- Prevalence of Coral Bleaching (two sanctuaries)
- Restoration Outcomes (e.g. Mission: Iconic Reefs)

5.2.4 Great Lakes–Specific Climate Indicators

- Mixed-Layer Dynamics Integrating: Water Temperature, Circulation, Wind Fields, Freshwater Discharge, Nutrient Concentrations, Storm Intensity

5.2.5 West Coast Region Physical/ Oceanographic Climate Indicators

- Upwelling Indices

5.2.6 West Coast Region Biological Climate Indicators

- Kelp Canopy Cover

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