Report of a Workshop on Best Approaches and Needs for Projecting Marine Mammal Distributions in a Changing Climate

Santa Cruz, California, USA
12-14 January 2016

Gregory K. Silber, Mathew Lettrich, and Peter O. Thomas (eds.)

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U.S. Department of Commerce
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Acronyms

CCE – California Current Ecosystem

CHL – Chlorophyll Concentration

ESA – Endangered Species Act

ETP – Eastern Tropical Pacific

FWS – U.S. Fish and Wildlife Service

IPCC – Intergovernmental Panel on Climate Change

IWC – International Whaling Commission

LMR – Living Marine Resources

MLD – Mixed Layer Depth

MMC – Marine Mammal Commission

MMPA – Marine Mammal Protection Act

MSE – Management Strategy Evaluation

NEPA – National Environmental Policy Act

NMFS – National Marine Fisheries Service

NOAA – National Oceanic and Atmospheric Administration

OSP – Optimal Sustainable Population

SDM - Species Distribution Model

SSH – Sea Surface Height

SST – Sea Surface Temperature

Definitions

Analogous species – similar or related species to a data-deficient species being modeled that provide insights to expected responses

Correlative models – species distribution models that relate species occurrence to environmental parameters

Empirical relationships – a correlation or relationship based solely on observation rather than theory

Envelope models – use of the observed range of environmental conditions as the definition of habitat

Forecast – most likely prediction (http://sciencepolicy.colorado.edu/zine/archives/1-29/26/guest.html)

Fundamental (potential) niche – The range of physiological tolerances for a species in the absence of interactions with other species (*e.g.*, competition, predation)

Generalized linear or additive models – statistical models that can be used to describe functional relationships between species distribution (occurrence or abundance) and environmental variables

Hindcast – a forecast made for a period in the past using only information available before the beginning of the forecast. (http://www.euporias.eu/taxonomy/term/89)

Model – a representation of reality

Nowcast – forecast on time scales of days to weeks

Prediction – probabilistic statement that an event will occur or condition will be present in the future based on initial conditions (http://sciencepolicy.colorado.edu/zine/archives/1-29/26/guest.html)

Process-based, or mechanistic, models – models built on assumptions about how a system works and are grounded in ecological theory

Projection – probabilistic statement that an event may occur or condition may be present in the future based on initial and future conditions (http://sciencepolicy.colorado.edu/zine/archives/1-29/26/guest.html)

Proxy variables – physical, environmental, or biological parameters that are readily observed or modeled and used as indicators for more complex processes or variables that are difficult to measure or model

Quasi-extinction threshold – an abundance below which the persistence of a species is unlikely

Realized (actual) niche – the environmental space where a species actually occurs; considers availability of environmental conditions and biotic interactions that influence a species distribution

Species distribution models – Extrapolates species distribution data in space and time from observations of species occurrences and environmental variables believed to influence the distribution individuals of that species. SDMs are usually based on a statistical model

Uncertainty – the degree to which a given state or outcome is not known, accounting for imperfect and unknown information

Executive Summary

Climate-related changes in marine and coastal ecosystems are already affecting fish, seabirds, and marine mammals. While the eventual magnitude of these climate-driven impacts remains unknown, alteration of oceanographic conditions and processes from global climate change are expected to profoundly influence ecosystems and marine mammals in the foreseeable future. As marine habitats undergo change, efforts to conserve marine mammals and manage marine ecosystems would benefit from the ability to anticipate likely responses of marine mammals to these changes. Research in this arena is in its infancy despite the critical need for methodologies to help anticipate changes in occurrence, distribution, phenology, and relative abundance of marine mammal populations so that conservation measures and ecosystem management can be developed accordingly.

The National Marine Fisheries Service (NMFS) and Marine Mammal Commission (MMC) convened a workshop in January 2016 to determine to what extent it is plausible to project climate-related changes in marine mammal distribution and relative abundance based on existing modeling practices and the current state of marine mammal science, and to identify the methodologies available and their limitations. The five workshop objectives were to:

a) explore modeling or other means to assess future changes in distribution and abundance of marine mammal species;
b) identify metrics relevant to assessing physical changes and biological responses of marine mammals;
c) identify one or more exemplar species/population(s) for assessing methodologies or metrics;
d) identify next steps for performing these studies; and
e) produce draft and final reports of the findings.

Given the global distribution and high mobility of many marine mammal species, the workshop assembled experts from various disciplines and provided the opportunity for collaboration among scientists (ecologists and modelers from marine mammal, fisheries, and climate science) and managers from the United States, Europe, and Australia. Though primarily focused on a U.S. perspective, the issues discussed in this workshop report can be applicable to other regions of the world and a number of marine mammal taxa.

Legislation in the United States and other nations specifically addresses the conservation and management of marine mammals. At the same time, governments are requiring increasing focus on ecosystem considerations within fisheries management, and marine mammals are often major predators in such ecosystems. The responsibility of managing marine mammals in the context of climate change will be driven by the quality of information available to managers. Effective communication between managers and scientists will be integral to developing and delivering information in management-relevant contexts. Resource managers must be able to identify research and analytical products needed from scientists, and scientists need to be able to convey

to managers the assumptions, strengths, and weaknesses in modeling studies and empirical research, and to provide clear statements regarding levels of uncertainty in projections.

A range of models, varying in levels of complexity, have been developed that can be used to generate projections of climate change impacts on living marine resources. These models vary in objective, form, informational needs, computational needs, and trade-offs. The three general classes of models commonly used to guide management decisions are expert opinion, statistical extrapolation, and process-based models. Expert opinion, or rule-based, models integrate information from a history of management applications and can be developed relatively rapidly in most cases; however, the assumptions used in these models are not always apparent. Statistical extrapolation models draw on species occurrence and data from past conditions of a particular system to project future conditions. Although the assumptions in extrapolation models are often transparent, past behavior of a system may not be suitable for projecting forward if the underlying ecological relationships are also sensitive to climatic conditions. Process-based, also called mechanistic, models are built on causal mechanisms grounded in ecological theory rather than correlation, which can increase the level of confidence in extrapolating beyond historical conditions. Mechanistic approaches have high computational costs and need to convey uncertainty regarding ways in which ecological processes are represented.

Choosing an appropriate model type for predicting future conditions is an important step in advancing research/management actions for a particular situation. Model selection will be based on criteria such as the extent of existing data related to the life history, distributional ecology, and population dynamics of the species; space and time scales of the required prediction; and whether existing models are based on environmental factors that can be projected into the future. Levels of uncertainty inherent to habitat and population dynamics models, in turn, are directly related to the amount known about a particular species' ecology and demography.

Because it is not possible to know precisely what the future holds, any prediction should identify some level of confidence in the likelihood that prediction will be realized. Estimating uncertainties in projected marine mammal responses to climate change and in the climate models (*i.e.*, various emission scenarios) themselves should consider whether and to what extent the model: a) is based on physiological and ecological principles expected to hold over the space and time scales of interest; b) adequately re-creates past (*i.e.*, hindcast) marine mammal responses to climate change over the space and time scales of interest; and c) captures primary uncertainties in marine mammal responses.

Data used in models are diverse (*e.g*., physical, biological, biogeochemical) and the amount of data available to address a particular question may vary. Situations can be characterized as data or model rich/poor. Mechanistic processes within a food web or ecosystem can be difficult to measure, and model and biological parameters or environmental data may be few or unavailable. These limitations have led modelers to search for simpler means, or proxies, to approximate certain processes. Physical oceanographic processes are more readily quantified and modeled than are ecological systems, and food web interactions and can serve as useful proxies for those processes. The breadth of data sources results in a variety of observed temporal and spatial resolutions and a range of confidence levels, but generally physical data can be measured with finer resolution and greater confidence than exist for the biological/ecological data. Physical proxies tend to accurately represent linkages to the physical environment for species feeding at low trophic levels, but may inadequately characterize relationships for marine mammals feeding at higher trophic levels.

A range of factors other than the physical environment will affect marine mammal modeling efforts, including trophic interactions, short-term behavioral responses, and anthropogenic influences. Some factors may be tractable within current modeling approaches, and they might be included in the initial baseline model. Some generalizations can be made for all marine mammals (*e.g.*, long generation times may make behavioral plasticity more important than evolutionary responses over the short term), while other features may be species specific (*e.g.*, degree of site fidelity to haul-out sites or migration routes). In contrast, some factors are difficult to model and might significantly alter model results. In particular, the ability of marine mammals to alter their behavior or food sources can act as a buffer to measurable climate-change induced changes, and can delay any adverse effects, or mask them until critical thresholds are reached.

Exemplar species should be identified now and used as case studies to begin forecasting future distributions. The workshop concluded that species or populations exposed to existing threats and vulnerable to large scale ecosystem shifts, represent a current management priority, or occur in rapidly changing ecosystems should receive most emphasis in the consideration of next-generation forecasting studies.

Discussion throughout the workshop identified activities and outcomes that would represent progress toward improving capacity to predict marine mammal distributions as the climate changes. It is essential to identify appropriate time scales for which a model will apply, recognizing that short-term “nowcasts” are likely to be more accurate than those projections out to decades or centuries. As data become available via ongoing monitoring and research efforts, model-based forecasts should undergo empirical validation. Given the global scale and complexity of both climate change impacts and marine mammal distributions, multidisciplinary collaborations will be necessary to develop new and improve existing models to enable a better understanding of the interplay between these processes. Finally, long-term fiscal planning will be critical to ensure scientists and managers are equipped with the tools and resources needed address the challenges of managing marine mammal populations in the future.

Introduction and Background

Marine mammals are exposed to a variety of threats and habitat perturbations from human activities on regional and global scales. Among these, alteration of oceanographic conditions and processes due to global climate change is expected to profoundly influence ecosystems and, in turn, marine mammal populations in the foreseeable future. While the nature and scope of these climate-driven impacts on marine mammals are uncertain, changes in the ranges and relative abundances of species or stocks are expected.

Long observational time series and modeling studies have illustrated distributional changes in some marine fish and invertebrate populations (*e.g.*, Nye et al. 2009, Pinsky et al. 2013, Poloczanska et al. 2013, Walsh et al. 2015) and climate change projections suggest the likelihood of further shifts (*e.g.*, Cheung et al. 2009, Stock et al. 2011, Gutt et al. 2012, Hare et al. 2012a, Hare et al. 2012b, Lynch et al. 2014). Some researchers have predicted that distributional shifts will occur in marine vertebrates, especially upper trophic level predators, due to climate change (IWC 2010, Hazen et al. 2013). Changes in regional abundance, distribution, and range in some marine mammal populations have been observed (*e.g.*, Hansen 1990, Angunuzzi and Buckland 1994, Heyning and Perrin 1994, Kovacs et al. 2011, Clarke et al. 2013), and there is a growing body of research on predictive studies involving marine mammals (*e.g.* Gilles et al. 2011, Becker et al. 2012, Keller et al. 2012, Gregr et al. 2013, Mannocci et al. 2014). Efforts to conserve marine mammals, and to manage human activities in marine ecosystems in general, would benefit from an improved ability to anticipate the response of marine mammal distributions to climate change.

Conservation of living marine resources (LMR) is often the responsibility of federal, state, and provincial governments. Legislation, such as the Marine Mammal Protection Act (MMPA) and Endangered Species Act (ESA) in the United States, authorizes agencies to develop regulations and protective (mitigation) measures for marine mammals. While agencies have broad authority to reduce threats, they may not always have the ability to do so quickly, due to limited resources, resistance to change by resource users, or regulatory inertia. In addition, threat-reduction measures may become obsolete, and it may be necessary to develop new or modified approaches in situations where LMR are undergoing shifts in regional abundance, under conditions of changing physical or biological ocean conditions and processes. Therefore, anticipating these changes through modeling would enhance near- and long-term planning by wildlife or resource management agencies.

Historically, ocean resource management practices have relied on site-specific "static management approaches" (*e.g.*, marine protected areas, coral reefs) (Hyrenbach et al. 2000) that precluded planning on time scales appropriate to ocean resource uses, dynamic ocean processes, and management of highly mobile organisms (Hobday et al. 2014, Lewison et al. 2015, Maxwell et al. 2015). As marine mammal habitats undergo change, wildlife management agencies will need to pursue conservation approaches that are responsive and flexible. However, strategies to pro-actively address changes on large geospatial scales are not easily developed.

For these reasons, there is a need to identify methodologies to aid in anticipating changes in occurrence, distribution, phenology, and relative abundance of marine mammal populations, so conservation and management measures can be developed accordingly. For example, in locations and situations where permitting (*e.g.*, for oil and gas, or offshore renewable energy lease-sales) is required, or where endangered species recovery planning is occurring, wildlife management agencies would benefit from the ability to predict changing marine mammal occurrence. Forecasts of future occurrences could inform the evaluation of the risks and benefits of various management responses. In some settings, marine mammals may also compete with humans for commercially valuable fish species. Therefore, advance knowledge concerning likely future shifts in distributions of significant predator species would be of benefit in deciding how to focus research to support fisheries and ecosystem management. In addition, for locations undergoing rapid ecosystem changes, including those in high-latitudes (Forcada et al. 2006, Laidre et al. 2008, Ragen et al. 2008), or where populations are in decline (*e.g.*, Shelden et al. 2015), resource management agencies will face challenges in responding quickly with effective protective measures.

> **Forecast –** prediction with highest likelihood of occurrence
>
> **Prediction –** probabilistic statement that an event will occur or condition will be present in the future based on initial conditions
>
> **Projection –** probabilistic statement that an event may occur or condition may be present in the future based on initial and future conditions
>
> (http://sciencepolicy.colorado.edu/zine/archives/1-29/26/guest.html)

These and related issues were highlighted by the National Marine Fisheries Service (NMFS) in its recently released Climate Science Strategy (Link et al. 2015), which identifies priority objectives and activities for managing LMR in a changing climate. One objective is to “identify future states of marine, coastal, and freshwater ecosystems, LMRs, and LMR-dependent human communities in a changing climate”. Near-term actions include adequately funding process-oriented research to improve understanding of climate impacts on these resources.

To investigate ways to address these needs, NMFS and the Marine Mammal Commission (MMC) convened a workshop on 12-14 January 2016 in Santa Cruz, CA, USA to determine whether projecting changes in marine mammal distribution and relative abundance was plausible based on existing modeling practices and current state of marine mammal science, and if so, to identify the considerations needed when making such projections.

Purpose of the Workshop

The purpose of the workshop was to identify and evaluate the analytical tools available for predictive modeling of marine mammal population distribution and assess the relative utility and precision of these tools as related to the conservation of marine mammal populations.

The stated workshop objectives were:

- Explore modeling or other means to assess future changes in distribution and abundance of marine mammal species;
- Identify metrics relevant to assessing physical changes and biological responses of marine mammals;
- Identify one or more exemplar species/population(s) for assessing methodologies or metrics;
- Identify next steps for performing these studies; and
- Produce draft and final reports of the findings.

The workshop consisted of ten invited presentations (see "Agenda", provided at the end of this report), associated discussion, and break-out group discussions. Presentations and subsequent discussions provided an overall background so participants with varied expertise had a baseline context on climate change modeling, ocean resource management, and marine mammal modeling studies to facilitate later discussions.

Here, we provide a report of workshop findings and conclusions that: a) synthesizes key points and conclusions from the invited presentations and break-out group discussions; b) provides context in regard to relevant literature; and c) identifies plausible next steps in forecasting marine mammal distributions. Rather than provide a meeting chronology, the report is organized by sections providing discussions of:

- regulatory context and the science/management interface;
- types of models and the considerations for selecting an appropriate model;
- uncertainty and model limitations;
- data types, data evaluation, and data limitations;
- characteristics of marine mammal species suitable for further modeling studies; and
- next steps and policy considerations.

In each of these sections, we provide descriptions of the background and context of a particular issue and approaches for addressing the issue.

Regulatory Context and the Science/Management Interface

The protection of LMR – including marine mammals and their habitats – is often legislatively-mandated to federal governments. In many instances, delegation of responsibility to agencies provides considerable latitude and a number of avenues for establishing protective measures (*e.g.*, McClure et al. 2013). It is under these jurisdictions that climate change-related impacts must also be addressed.

Relevant Legislation and Federal Agency Activities

In the United States, the U.S. Fish and Wildlife Service (FWS) and NMFS are the primary agencies charged with the protection and recovery of organisms designated as threatened or endangered on the ESA List of Endangered and Threatened Wildlife (50 CFR 17.11) (http://www.fws.gov/endangered/laws-policies/). The MMPA "prohibits, with certain exceptions, the 'take' of marine mammals in U.S. waters and by U.S. citizens on the high seas" (http://www.nmfs.noaa.gov/pr/laws/mmpa/). Among other things, the MMPA allows the granting of "Incidental Take Authorizations" to activities such as oil and gas development, exploration, and production; geophysical surveys; and other activities when no more than a "negligible impact" on those marine mammal species or "stocks" is expected to occur. The MMPA also requires that all marine mammal stocks are identified, their status monitored, and measures taken to ensure that stocks return to, or do not decline from, their Optimum Sustainable Population levels. Marine mammal stocks are typically defined by static geographic ranges.

In 1970, the U.S. Congress passed the National Environmental Policy Act (NEPA) into law; its stated goal is to "formulate and recommend national policies which ensure that the programs of the federal government promote improvement of the quality of the environment" (www.gsa.gov/nepa). Federal entities such the U.S. Army Corps of Engineers, the U.S. Navy, and the Department of the Interior's Bureau of Ocean Energy Management are responsible for adhering to requirements of NEPA, which includes, among other things, assessments of cumulative impacts from all sources including climate change. Under the ESA, these entities are to consult with the appropriate agency (*i.e.*, FWS or NMFS) "to ensure that actions they authorize, fund, or carry out do not jeopardize the existence of any species listed under the ESA, or destroy or adversely modify designated critical habitat of any listed species."

Related to this, interactions between marine mammals and fisheries fall under the jurisdiction of the federal government. Regulations under the MMPA and Magnuson-Stevens Fishery Conservation and Management Act aim to reduce incidental bycatch of marine mammals by fisheries. Fisheries stock assessment reports include ecosystem effects, such as depredation by marine mammals or competition between marine mammals and the fishery.

Other nations (as well as state or provincial governments) have analogous legislation and capacities to establish protective measures, but with varying levels of scope. In Canada, marine mammals are managed under the Species At Risk Act and by development of Marine Mammals Regulations under authority of the Fisheries Act. Australia manages marine mammals under the Environment Protection and Biodiversity Conservation Act of 1999. New Zealand has managed marine mammals since 1978 under the Marine Mammals Protection Act. Marine mammal management in the United Kingdom is authorized by the Offshore Marine Conservation Regulations of 2007 and the 2010 Conservation of Habitats and Species Regulations (as amended). These are but a few examples; many nations have related laws. Therefore findings presented here are likely to have application for resource management in waters of a number of countries.

In most cases, in the United States in particular, these laws, and the policies developed under them, not only provide considerable leverage in developing conservation programs, but also require federal agencies to take into account all forms of potential impacts on marine mammal populations that may arise from planned activities (*e.g.*, industrial, military, or research operations). Among these is the impact of global climate change. For example, under NEPA, ESA, and MMPA, NMFS is expected to consider climate change in recovery planning, assessments of threats with regard to permits for endangered species and habitat conservation plans, and the permitting of various ocean-based human activities. Under the ESA in particular, a recent agency-wide directive requires that NMFS take into account factors related to climate change when making determinations regarding:

- adding a species to (or removing it from) the ESA's List of Endangered and Threatened Wildlife;
- conducting listed endangered species status reviews;
- designating critical habitat;
- undertaking recovery plan evaluation and analyses;
- permitting take of listed species; and
- consultations with other agencies regarding the impacts from various activities.

Agency management actions occur on varying temporal and spatial scales. Mitigation of marine mammal exposure to military operations (*e.g.*, NOAA 2015), measures to reduce large whale entanglement in commercial fishing gear, and ship strike prevention are often established in specific areas and seasons (*e.g.*, Silber et al. 2012), and may only be implemented on the scale of seasons or a few years (NOAA 2013). Endangered species recovery plans are developed with annual cost estimates for the first five years and are to be updated at least once every five years. Planning and permitting for industrial activities such as the siting or construction of offshore renewable energy facilities and oil and gas exploration and development tend to be on the order of decadal periods. On still longer time scales, ESA listing decisions often assess the prospects for species persistence on the order of a century (*e.g.*, Angliss *et al*. 2002). For example, one of the recovery criteria for the North Atlantic right whale (*Eubalaena glacialis*) is "…no more than a 1% chance of quasi-extinction in 100 years" (NMFS 2005).

Endangered marine mammal ESA listing determinations can have management implications that are global and multi-decadal in scale. Dozens of marine mammal species were designated as endangered with enactment of the ESA over 40 years ago. Listed large whale species designations were range-wide, *i.e*., global. Although some populations have been re-designated (*e.g*., eastern North Pacific Steller sea lion (*Eumetopias jubatus*) and gray whale (*Eschrichtius robustus*)) or proposed for re-designation (humpback whales (*Megaptera novaeangliae*)), most other listed species are expected to retain their current designations for the foreseeable future. Therefore, these designations will involve ongoing management responsibilities that are global in scope and lasting for decades.

Thus, in the context of the scope of responsibilities entrusted to wildlife conservation agencies, an ability to forecast marine mammal relative abundance and distribution across relevant spatial and temporal scales have the potential to enhance marine mammal conservation practices. Given the range in spatial and temporal scales embedded in these mandates, scientists and resource managers can expect to face challenges in selecting appropriate temporal and spatial scales for modeling studies as these animals' habitats undergo change.

Science/Management Interface

In any science-based resource management endeavor, research enterprises should be aligned with management needs and objectives. Managers, policy-makers, and researchers all have critical roles to play in understanding the impacts of climate change and managing marine mammal populations. Managers are guided by legislative, policy, and operational objectives using data collected and analyzed by researchers combined with social, economic, and political considerations. Researchers seek to gather information needed to inform, elucidate uncertainties, and make recommendations around decision-making.

There is not a one-to-one or perfect connection between scientific inquiry and production of scientific results relevant to specific decision-making challenges. In terms of modeling studies, temporal and spatial scales of modeled outputs may be difficult to match to the temporal scales or spatial resolution required for management decisions (*e.g.*, Griffis et al. 2008). For example, managers may be seeking information about future prospects for a marine mammal stock occupying a small range, but available habitat and distribution models may only provide projections for much larger study areas and spatial scales. In another example, a model with the power to predict presence or absence of a species from one season, or year, to another may not serve to inform long-term trends in the presence of that species required for making a listing determination under the ESA.

In addition to these differing objectives, disconnects between managers and researchers occur for several reasons. First, scientists might build distribution models outside of decision-relevant contexts. Second, managers may not clearly articulate their needs and communicate these to scientists so that models and analyses best meet those needs. Finally, even if decision-makers and researchers are in close consultation on research needs, only limited data may be available. In each of these cases, model output, no matter how robust, may be of limited use to specific management challenges.

It is also essential that policy-makers understand the role of uncertainty in modeling (discussed below). Scientists need to ensure that the uncertainty inherent in a modeling effort to inform a given management issue is presented in a way that: a) is simple to understand; b) is based on parameters that can be estimated readily and evaluated; and c) provides metrics that can be translated into transparent, rational management decisions or action thresholds (Taylor et al. 2000). Ultimately, doing so allows the development of more informed management approaches and decision criteria, despite the fact that some sources of uncertainty may be difficult or impossible to reduce within timeframes required for management. Managers may wish to evaluate a range of decision criteria to assess likely success or failure of a variety of possible management approaches within a risk analysis (cost-benefit, or worst case scenario) framework. Scientists can aid the development of management strategies by conducting targeted simulation studies or sensitivity analyses to assess probabilities of achieving management objectives under various decision thresholds (*e.g.*, 'minimum population size' under the MMPA; Wade 1998).

In addition, data-collection needs chronically outpace available funding. Given that climate change is not the only threat confronting marine mammal conservation, it is critical that agencies allocate resources for research and monitoring to provide the best possible information to inform management decisions. Alignment of science and policy needs will support allocation decisions where funding is available and may help identify future funding needs.

Given the considerations discussed above, the workshop addressed the interplay of information needs with the current realities of modeling horizons, in time and geographical scale, and levels of uncertainty as a means to characterize the framework for such efforts. These issues are discussed in the sections that follow.

Aligning Resource Management Needs and Modeling Time Periods – A Visual Approach

Aligning research objectives, particularly modeling efforts, with resource management needs can best be accomplished by explicitly identifying the temporal and spatial scales over which both operate. Here, we graphically present various management activities for which future marine mammal distribution is relevant and the research approaches for predicting distribution along spatial and temporal axes (Fig. 1). The approach is inspired by the Stommel (1963) diagram which has been used to map fisheries management activities in a similar fashion (Dunn et al. 2016); however, we believe there has been no previous attempt to plot management and research activities in this way. We note that this approach could be valuable for numerous types of scientific endeavors, not just distribution projections.

As indicated by the graphic, modeling on a long time frame, as in the case of evaluating threats under the ESA for long-lived species, leads to broad, general predictions that may be most applicable to large geographic areas and at species levels. Such long-term modeling does not have equal precision in discerning trends for smaller populations within a species. Population trends or changes in geographic distribution at the smaller scale may be driven by more proximate factors which, while important to populations, have less effect on larger species-wide trends. At the opposite end of the spectrum, short-term changes in population size or geographic distribution may be discernible at small geographic scales, but carry little predictive power for long-term trends.

At large-scales, direct use of global climate change projections can be tractable (Randall et al. 2007, Stock et al. 2011) but applications at local scales may require investment in high-resolution climate models and/or downscaling exercises (Saba et al. 2016). There are certain limitations involving assumptions associated with downscaling discussed later in this report. Nonetheless, other cases exist in which marine mammal-associated modeling and management align well, such as for large whale ship strike reduction efforts that require short-term projections of distribution over a small area (*e.g.*, Redfern et al. 2013). These cases have proven tractable at relevant spatial scales for some environmental drivers (*e.g.*, sea surface temperature (SST) anomalies, Hobday et al. 2011, Spillman et al. 2013, Stock et al. 2015).

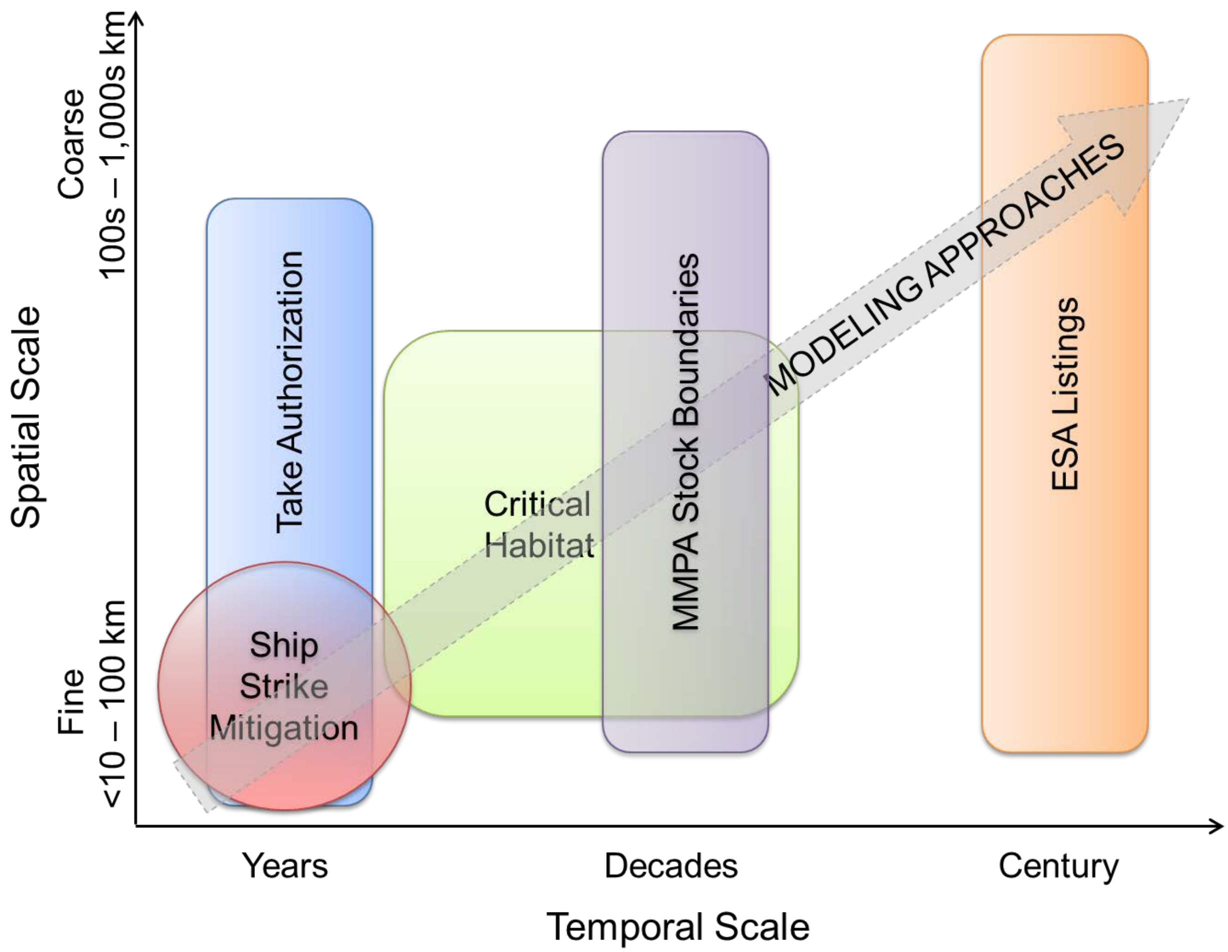

Figure 1. Conceptually, several illustrative marine mammal management activities are mapped along temporal/spatial scales, overlain (gray arrow) with a generalized characterization of the state of species distribution models. The temporal and spatial precision of predictive efforts decreases at longer time scales and larger spatial scales. Short-term projections on relatively

small spatial scales will have greater granularity than projections on long time and large spatial scales. Management and research objectives on appropriate spatial/temporal scales will dictate model type selection and data used.

Communicating Management and Research Needs

Clear articulation of temporal and spatial scales of analysis of future marine mammal distribution required to inform specific management decisions will assist the development of relevant modeling efforts. Likewise, clear indications by scientists of the limitations of predictive power at different scales will improve the tailoring of research to management requirements and accelerate the use of research results in management action. Awareness of these challenges will also improve communication of management needs, and the nature of the science required to meet those needs, to funders, the public, and other stakeholders (including other researchers and agencie). Scientists preparing research proposals will be better able to tie proposed activities to identified management needs, and agencies will be better able to articulate funding requests on the basis of clearly identified priorities. NMFS Science Centers, for example, may be able to use this process to identify existing and ongoing research programs that may need adjustment to be better take into account management needs.

Another benefit of this conceptual approach is that it helps guide research prioritization in at least three areas. First, studies are needed to test model assumptions. For example, a model that predicts future habitat for an Arctic species based on future projections of sea ice inevitably involves assumptions about how the species (and individuals) will respond to those changes in sea ice, particularly at key life stages. These assumptions can be tested by conducting "process" studies to determine how the species (or individual) actually does respond in areas where ice loss is occurring most rapidly within their range. Ideally, such results help to clarify functional responses of species and can be incorporated to improve model projections. Similar evaluation is needed to assess the relevance of any underlying physical data or models. These evaluations will largely be conducted by physical oceanographers, climate scientists, and biological oceanographers on collaborative modeling teams. A second element is that of basic monitoring, which can be directed to testing model predictions. For example, if a model being considered as a basis for management decisions makes specific predictions about marine mammal range change, field studies should be directed to determine whether those predictions are being realized. Targeted studies involving specific data collection needs (quantifying the occurrence of a particular species in a particular location, for example) might be identified. Third, model results can also be used to direct research priorities in the absence of information. In this instance, provisional models with recognized shortcomings and untested assumptions may arguably be an improvement over acting on the basis of little information of any kind. For example, such a model may assist in identifying stocks and geographic areas where the rates of distribution changes are projected to be most rapid. This can focus the design of research and monitoring efforts to document climate-driven changes in distribution.

Case Study: Projecting Ringed Seal Distributions

In some cases, particularly for ESA listing decisions, the 'best available science' will include a broad consensus among climate scientists about future trends in key factors that will influence a species' or population's future distribution.

Ringed seal distributions were projected through the 21st Century by using a highly simplified definition of habitat required by the species for the critical life history functions of whelping pups and nursing them to independence. These functions occur during spring, a period when the pups are highly vulnerable to predation and hypothermia if there is insufficient snow cover in which the mothers can construct and maintain lairs on top of the ice. Studies of lair construction indicated that accumulated snow depths of at least 20 cm are required for drifts to form that are sufficiently deep (50–65 cm) for adequate birth lairs. Therefore, ringed seal habitat and breeding distribution were assumed to be those areas of the Arctic where at least 20 cm of snow depth could be expected in the month of April. Output from global climate models predict that although precipitation in the Arctic is expected to increase, much of it will fall as rain, and delayed autumn ice formation will mean that some of the snow will fall into open water rather than accumulating on the ice surface. The area with snow depths above 20 cm in April was projected to decline under a broad range of plausible greenhouse gas emission scenarios, up to 70% by the end of the 21st Century under one emissions scenario (Hezel et al. 2012). This would reflect a substantial loss of ringed seal reproductive habitat.

The strength of an approach like this is that it is built upon climate projections that are, qualitatively at least, broadly agreed to represent the best available science. One significant limitation is that characterization of ringed seal habitat has been reduced to just one or a couple of dimensions (sea ice extent and snow accumulation).

Types of Models and Selecting Appropriate Models

A primary objective of this workshop was to identify approaches that can be used to project marine mammal distributions. In this section, we discuss a variety of modeling approaches that can be and have been used to forecast species distributions. We further discuss factors that should be considered when selecting the most appropriate model for a given application.

Typology of Models

A broad range of models has been developed that can be used to generate projections of climate change impacts on LMR. Ranging from simple to complex (Table 1), these models have different objectives and form; they also have different trade-offs (Morin and Thuiller 2009, Stock et al. 2011). Traditional single-species stock assessment models are the basis for many management efforts and focus on the dynamics of a target organism. Other modeling approaches emphasize interactions between organisms and between organisms and their environment.

Table 1. Model types. Examples of models and their various characteristics.

Model Approach	Characteristics	Selected References
Observation		
Historical records	Presence only data, point maps of observations, broad spatial scales (*e.g.*, museum collections, ships' logs)	
Range maps or kernel density	Presence only data, converts point data to a continuous surface of point density, interpolation, broad spatial scales (*e.g.*, home range maps)	
Grid-based surveys	Divides study area into equal-area grid cells, systematic data collection, generally presence only data due to coarse spatial scale	
Expert Based		
Expert opinion, published literature	Observations on species abundance are lacking but environmental data exist, uses simple decision rules to define species habitat requirements	
Vulnerability assessment	Life history characteristics and predicted exposure to climate change are combined for a number of species within a region to create a relative vulnerability index	
Statistical		
Envelope methods	Uses statistical correlations between observed species distribution(s) and environmental variables to define species tolerance, envelope drawn around some percentage of observations (often 95%) (*e.g.*, BIOCLIM, broad spatial scale)	Hazen et al. 2013 Hobday 2010 Kaschner et al. 2006
Quotient	Numerically calculates probability of species occurrence or abundance along an environmental gradient.	Eveson et al. 2015
Environmental Niche	Uses computer algorithms to predict distribution of species in geographic space based on a mathematical representation of known distribution in environmental space (realized ecological niche), presence only data, allows for interpolation if data are few (*e.g.* MaxEnt)	Merow et al. 2013 Druon et al. in press
GLMs (generalized linear models)	Linear regression based models, uses a transformation to cope with non-normal distributions of response variable (x)	Becker et al. 2010 Forney et al. 2012
GAMs (generalized additive models)	Non-parametric extensions of GLMs, flexible and automated way to identify/describe non-linear relationships between predictors and response	Becker et al. 2012, 2014, 2016 Ferguson et al. 2006 Forney 2000

Spatial regression	Regression method that explicitly includes spatial information related to observations, important for highlighting spatial processes in data, spatial effects incorporated via spatially lagged independent variable, spatially lagged dependent variable, or spatially lagged error term	NOAA 2012 See "Case Study: Projecting ringed seal distributions" text box in this report
Machine Learning		
Regression Trees	Numeric or continuous response variable, fits regression model to response variable using each independent variable, for each independent variable data are split recursively	Dell et al. 2015
Process-Based (Mechanistic)		
Atlantis	A modular whole-ecosystem model based on the Management Strategy Evaluation approach that incorporates biophysical, economic, and social processes	Fulton et al. 2004
Models of Intermediate Complexity for Ecosystem assessment (MICE)	More complex than single-species models but less complex than ecosystem models. Includes ecological processes and can be connected to non-ecological models	Plaganyi et al. 2014
SEAPODYM (Spatial Ecosystem and Population Dynamics Model)	Numerical model initially developed for investigating physical-biological interactions between tuna populations and the pelagic ecosystem of the Pacific Ocean	Lehodey et al. http://www.spc.int/ofp/seapodym
APECOSM (Apex Predators ECOSystem Model)	Goal to represent spatialized dynamics of open ocean pelagic ecosystems in global ocean	Maury et al. http://meece.eu/library/APECOSM/apecosm.html

There are three general classes of models commonly used to guide management decisions: expert opinion, statistical extrapolation, and process-based models. Expert opinion or rule-based models are used most where a need exists for repeated response to management problems that remain similar over time. This approach facilitates integration of legacy information from a history of management applications and can be developed relatively rapidly in most cases. However, there may be little potential for evaluating the assumptions used in these models because assumptions behind expert opinion are not always apparent.

Statistical extrapolation models draw on data from past conditions of a particular system to project future conditions. These models may utilize, for example, species occurrence data, and climatic conditions at those locations, to create correlations that are used to extrapolate the future range of species under climate change. Although the underlying assumptions of extrapolation models are often transparent, models based on the past behavior of a system may not be suitable for projecting forward if these underlying ecological relationships are also sensitive to climatic conditions.

Process-based, also called mechanistic, models rely on explicit assumptions about how a system works and are grounded in ecological theory. These are built on causal mechanisms rather than correlation which can increase the level of confidence in extrapolating beyond known data and can allow for the partitioning of uncertainty in predictions. Nonetheless, use of mechanistic approaches has constraints due to high computational costs (owing to the model's complexity), reliance on assumptions that conditions will persist into the future, and the need to incorporate uncertainty regarding ways in which ecological processes will respond to novel global conditions.

Below, we provide descriptions of some models discussed at the workshop with application to modeling marine mammal occurrence. A fuller description of the range of models available and their uses and limitations can be found in Redfern et al (2006), Plaganyi et al. (2007), Stock et al. (2011), and Cuddington et al. (2013).

Expert-Based Models

Modeling options are limited for those species for which little ecological information is known, and in such cases, conceptual models based on expert opinion are the best choice. In general, forecasts from such efforts will be based on a conceptual distribution map and expert opinion on how the distribution may be affected by climate change. Uncertainty in such predictions will be high and difficult to describe quantitatively.

An example of a simple conceptual model that relies only on a description of a species' distribution is the seasonal distribution of North Atlantic right whales described by Winn et al. (1986), who identified the regions where the animal occurs at different times of the year based on known sightings records. In this case, relatively simple characterizations of seasonal occurrence were displayed visually.

Vulnerability assessments often utilize expert judgment to cope with gaps in observational data and predictive capability. Vulnerability assessments incorporate exposure, sensitivity, and adaptive capacity of a suite of species to generate an overall vulnerability rank. Laidre et al. (2008) provided an example of assessing one of the components of climate vulnerability, sensitivity to climate change, for Arctic marine mammal species. NMFS is currently developing a trait-based, semi-quantitative climate vulnerability assessment methodology for marine mammals that uses a mixture of expert opinion and empirical data to generate relative vulnerability ranks among species and highlight those traits and exposure factors that most contribute to species climate vulnerability.

Statistical Models

The availability of sighting data and environmental information increases the variety of statistical approaches that can be used to construct habitat models. Each type of modeling approach seeks to relate the occurrence or abundance of a species with particular environmental conditions; suitable habitat is assumed to occur where those conditions exist. The simplest of the approaches are correlative envelope models, which use the observed range of environmental conditions where species occur to define habitat. For example, if most bottlenose dolphins (*Tursiops truncatus*) occur between SST of 10-15º C, then a map of all locations with surface temperatures between 10-15º C is a map of suitable bottlenose dolphin habitat. Kaschner et al. (2006) used envelope models based on observed relationships between basic environmental conditions and a given species' presence to predict the average annual geographical ranges of marine mammal species on a global scale.

In essence, these models are descriptive – based on a statistical relationship between a species and the environment. Species distribution can then be "predicted" under specific environmental conditions based on the statistical relationship. These models assume that the statistical relationship is unchanging (*i.e.*, stationary). Such models are effective at predicting a species' fundamental niche (the set of environmental conditions under which a species can survive; Hutchinson 1957) but may not accurately capture the species' realized niche (*i.e.*, the species' actual distribution that reflects predator and prey dynamics, interactions with the physical environment, historical events, and other factors). The realized niche is most relevant in the conservation and management context.

More sophisticated statistical techniques, such as generalized linear or additive models, fit functional relationships between species distribution (occurrence or abundance) and environmental variables (*e.g.*, as surface temperature increases from 10 to 15º C, the abundance of bottlenose dolphins increases in areas exhibiting those temperatures, but in waters with surface temperature greater than 15º C, bottlenose dolphin abundance remains constant). Maps of habitat showing spatial/temporal variability in the probability of occurrence or abundance can be generated from these statistical relationships. Predictions of a species' distribution can be generated using expected future values of the environmental variables used in habitat models (*e.g.*, Becker et al. 2012). As an example, predictive habitat-based models for 11 cetacean species in the California Current Ecosystem were developed using a variety of dynamic environmental variables, including temperature, salinity, sea surface height, and mixed layer depth (Becker et al. 2016; see "Case Study: Modeling cetacean density in the Pacific Ocean" below).

Process-Based or Mechanistic Models

Process-based models are based on a theoretical understanding of relevant underlying ecological processes. These models provide a way to predict an organism's specific response to altered environmental conditions and an ability to extrapolate beyond known conditions. These features make process-based approaches well-suited to guiding management decisions under conditions of rapid global change (Cuddington et al. 2013).

In the last two decades, technical advances in observational data collection and access to large environmental databases have enabled shifts from simple exploration of correlations between marine mammals and their environment toward models that established functional relationships with the physical and biological underpinnings of habitat utilization (Gregr et al. 2013, Cribb et al. 2015). This, in turn, has led to increased use of process-based modeling and increasingly robust predictions of species distributions rooted in ecological understanding (Palacios et al. 2013). When constructing process-based models it is essential to consider ecological processes relevant to the species under study, the scientific questions being addressed, and appropriate spatial/temporal scales.

Recent examples of this approach include modeling California sea lion (*Zalophus californianus*) habitat utilization and foraging success based on biogeochemical, regional ocean circulation, and forage fish submodels (Fiechter et al., in review). Baumgartner and Mate (2005) used water depth, depth gradient, bottom hydrographic properties, SST, chlorophyll concentration, and other features to characterize North Atlantic right whale habitat.

Choosing a Model

Choosing the appropriate model to assist in predicting future conditions is an important step in pursuing a research/management endeavor for a particular situation. As indicated earlier in this report, developing various models and model type selection will be based on such things as *a priori* knowledge of and existing data related to the life history, distributional ecology (*e.g*., prey preferences), and population dynamics of the species of concern; the state of model development for the species of interest; the space and time scales of the required prediction; observational constraints for evaluating past model performance; and whether existing models are based on environmental factors that can be projected into the future (Fig. 2). Levels of uncertainty inherent to habitat and population dynamics models, in turn, are directly related to the amount known about a particular species' ecology and demography. In some instances, use of proxies for certain unknown variables may be the best (or only) approach. If sufficient analytical time and funding are available, and the abundance, distribution, and behavior of a species and relevant other variables (*e.g*., oceanographic) are known, multi-disciplinary teams should be assembled to assess modeling options and the ranges of forecasting ability (Fig. 2).

Choosing a Model – Modeling Issues and Obstacles

In this section we review some of the major elements and concerns involved in modeling. We first discuss general conclusions about the difficulties of modeling marine mammal distribution and response to climate change; then, address uncertainty and model limitations, data types and their limitations, and use of physical data proxies. The section concludes with a summary of features unique to marine mammals which may be intractable in modeling.

A key discussion area at the workshop was the extent to which certain SDMs can be useful for predicting future marine mammal distribution. Participants indicated that a variety of marine mammal characteristics introduce uncertainty into modeling efforts. As long-lived endotherms, marine mammals are not tied tightly to specific physical environmental characteristics, and the behavior of individuals -- and the ability of individuals to respond to change within the course of a season or lifetime -- introduces variability that may be difficult to capture in modeling efforts encompassing only a few marine mammal generations. As discussed below, this limits use of proxy variables that might otherwise be effective in modeling low trophic level responses that influence marine mammal distributions. While some groups, such as the baleen whales that feed on lower trophic levels may exhibit tight coupling to environmental variables, odontocetes feeding at higher trophic levels may not. These considerations need to be addressed in any modeling study, and tempered the workshop's overall expectations about the ease and utility of modeling approaches to predict future distributions of marine mammals at the scale of climate change.

Various models used to predict impacts of climate change on marine organisms (and discussed in this report) may not be appropriate for all marine mammal species. In an important example, the primary climate-related threat to Hawaiian monk seals (*Monachus schauinslandi*) will likely be sea level rise and loss of vital haul-out areas. Therefore, a wholly different type of modeling (dynamic shoreline evolution) would be appropriate for forecasting their future distribution.

Participants reviewed case studies presented at the meeting. In particular, the work of Forney et al. (2012) provided state-of-the-art modeling in well-characterized ecosystems with species for which distribution and abundance are known from systematic survey efforts (see text box on "Case study: Modeling Cetacean Density in the Pacific Ocean"). This work is of value in providing real-time and seasonal or annual predictions of the presence of a number of marine mammal species in the California Current ecosystem. On a much longer time scale, biological opinions developed in support of ESA listing decisions for Arctic marine mammal species provided the most relevant example of modeling on large spatial and long temporal scales (see text box).

Between these two extremes there are few examples of modeling and prediction in the medium term. In fact, the workshop drew to a large extent on studies involving marine fish and invertebrate species to provide context for this type of analysis. In these studies, historical catch data and other information were used to quantify shifts in distribution to date and to project expected distributional changes (*e.g.*, Hare et al. 2012a, Pinsky et al. 2013). However, because marine mammals differ in life histories from these taxa, and due to a paucity of ecological or (regional-scale) distributional data for many marine mammal populations, this type of analysis may not be possible for marine mammals in the near term. Therefore, the workshop concluded that one of the most effective ways forward for studies involving marine mammals will be to continue to expand the capabilities of current short-term modeling efforts to encompass longer time-frames and larger areas, and perhaps to narrow the geographical scale of modeling (*e.g.*, from circumpolar to regional basins) for populations for which broad scale predictions have been developed on decadal or centurial time frames.

When is the projection needed?		Existing Knowledge and Data	
		Poor	Rich
	Later	Collect data and study species	Establish multi-disciplinary team to develop model
	Now	Utilize expert opinion	Utilize existing model of appropriate complexity

Figure 2. Decision matrix for choosing an approach based on project timeline and available data.

The Continuum of Existing Knowledge

Redfern et al. (2006) described habitat modeling along a continuum of ecological knowledge for a given cetacean species (Fig. 3). For species about which little knowledge exists, habitat models based on scant data may be strengthened by the use of expert opinion to describe species' distributions on coarse time and space scales. As knowledge improves, habitat models can be made more detailed and quantitative, and can be used to predict distribution over short temporal and small spatial scales. For some species (*e.g.*, a suite of cetacean species occurring in waters off the U.S. west coast (Becker et al. 2012, Forney et al. 2012), and in New England waters (Best et al. 2012)), considerable work has been done to develop habitat models; these species are good candidates for making limited projections of future distributions. With a high level of ecological knowledge, habitat models can be used to develop specific testable hypotheses for process-based studies, which would in turn provide data and results to improve habitat models and lead to refined hypotheses for future testing.

Models based on empirical relationships (*i.e.*, involving a correlation or relationship based solely on observation rather than theory) are considered reliable for short time-scale predictions where conditions over the predicted time-scale are not expected to evolve beyond the range of observations. Myers (1998) noted that such relationships may break down even over short time-scales; thereby indicating the importance of understanding mechanistic relationships (*i.e.*, those founded on ecological processes) for even short time horizons. Therefore, for multi-decadal climate change applications, mechanistically informed empirical relationships provide a starting point, but projections based on robust physiological and ecological principles expected to hold under climate change are essential for building confidence in future projections (Stock et al. 2011). Mechanism-driven models that identify trophic links between oceanic processes, prey, and cetaceans have been limited to planktivorous species with very short trophic linkages (*e.g.*, Baumgartner et al. 2003, Croll et al. 2005). Iterative sequences of hypothesis testing and improvement of habitat models enhance spatial ecology predictions (Palacios et al 2013). The addition of improved physiological/ecological elements should be done iteratively as new insights are gained (*e.g.*, Cheung et al. 2009, 2010) as long as a frank assessment of remaining uncertainties is always provided, including those in the climate (*i.e.*, emissions) scenarios themselves.

Irrespective of the current understanding regarding a particular group and its relationship to its physical or biological environment along the knowledge continuum, the goal of an incipient modeling effort is to build knowledge to the point where a model of a species' distribution can be developed and its "nowcast" capability validated. At this point the potential for using the model for decadal or centennial forecasts can begin to be explored.

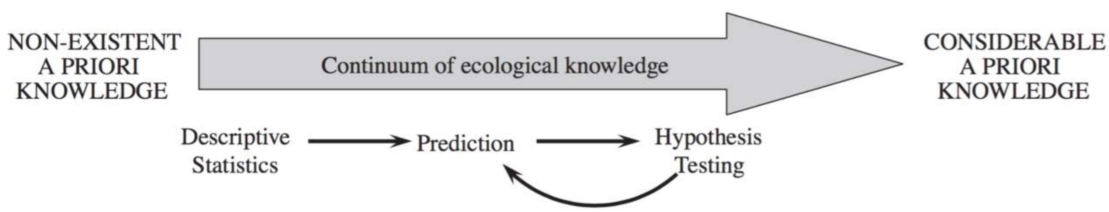

Figure 3. Models can be used to increase ecological knowledge through iterative hypothesis (from Redfern et al. 2006).

Uncertainty and Model Limitations

Best practices for developing and using projections of marine mammal responses to climate variability and change include careful assessments and communication of confidence and uncertainty inherent in those analyses (see Stock et al. 2011). Quantitative and qualitative results of confidence assessments are essential for informing management decisions, evaluating management strategies, and providing a basis for risk analyses (Smith et al. 1999). The most successful management approaches are those that explicitly incorporate uncertainty (*e.g.* Taylor et al. 2000).

Strengths and weaknesses inherent to both the information incorporated into models and the ensemble of outputs determine the role of uncertainty in quantities of interest (*e.g*., future population size, likelihood of ice loss). As noted, a clear understanding of these factors helps managers interpret the scientific information and also helps prioritize data needs.

Because it is not possible to know precisely what the future holds, any prediction should identify some level of confidence in the likelihood that prediction will be realized. People are provided with this kind of information in short-term weather forecasts that are presented in terms of "percent chance of rainfall" for specific places and time frames. Likewise, seasonal climate forecasts are couched in terms of probabilities for specific outcomes with, for example, statements like "the upcoming winter has a 60% chance of being wetter than normal in southern California, a 25% chance of being normal, and a 15% chance of being dryer than normal." Statements about uncertainty might also include indications of levels of confidence around an expected percent change in a particular forecast. Following the previous illustration, this would be expressed as "the upcoming winter has a 60 ± 5% chance of being wetter than normal."

Three main sources of uncertainty in global climate projections are the evolution of factors forcing climate change (*e.g*., greenhouse gas emissions), climate model differences, and natural variability. Multiple forcing scenarios might be used to account for these uncertainties and are generally constructed using projections with the same climate model and emissions scenarios (*e.g*., Nakicenovic et al. 2000, IPCC 2007, Moss et al. 2010) but different initial conditions. Even slight differences in initial conditions can result in rapid divergence of outputs. The result is an array of climate change scenarios with a range of outcomes (Knutti and Sedláček 2013) where, in some cases, even the direction of change in key variables may differ. Uncertainties in the biological response to climate variability compound uncertainties in projected climate forcing (Cheung et al. 2016). Downscaling global climate projections to regional scales, in which regional-scale climate projections are extended to biological impacts, may also increase this uncertainty.

Estimating uncertainties in projected marine mammal responses to climate change and in the climate models themselves should consider whether and to what extent the model: a) is based on physiological and ecological principles expected to hold over the space and time scales of interest; b) adequately re-creates past (*i.e.*, hindcast) marine mammal responses to climate change over the space and time scales of interest; and c) captures primary uncertainties in marine mammal responses.

Predictions over short time-scales (*i.e*., days to seasons) generally allow for testing of the stability of ecological principles over time and space and, because predicted conditions are often within the range of past variations. Climate change projections, in contrast, can often be tested against very limited knowledge of past long-term trends and must project into novel oceanographic conditions. Testing for confidence must thus rely heavily on the stability of ecological underpinnings and confidence is reduced by empirical relationships that lack strong mechanistic foundations.

Assessment of modeled marine mammal response to climate change should emphasize testing over similar space- and time-scales in a manner that mimics the eventual prediction as closely as possible. Use of separate data sets to test and train a model (or, out-of-sample testing) is important for short time-scale predictions. Testing against existing knowledge of past climate change responses or observed responses is emphasized for longer time-scale projections. Consultation with experts provides the initial foundation for assessing each of these variables and should allow development of a clearly articulated rationale for the model structure and permutations in its structures. Sensitivity analyses may be needed to assess uncertainty under a number of alternate scenarios. However, even a single projection can be useful in elucidating the magnitude, direction, and potential mechanisms underlying projected changes.

Case Study: Modeling Cetacean Density in the Pacific Ocean

NOAA's Southwest Fisheries Science Center (SWFSC) has developed and validated predictive habitat-based density models for cetaceans using an extensive line-transect survey data set that covers broad areas of the eastern Pacific Ocean (Fig. A). Their work includes a variety of projects that have advanced the science of species distribution modeling in several key areas, including comparing the effectiveness of various modeling frameworks, evaluating different spatial and temporal resolutions of input variables, and developing methods to characterize uncertainty in model predictions (Barlow et al. 2009). Models have been developed and validated for 25 species or species groups in three broad study areas - the California Current Ecosystem (CCE), the eastern tropical Pacific (ETP), and the central Pacific (Fig. A; Forney et al. 2012, 2015; Becker et al. 2016). Model validation has included internal cross-validation during the model selection process (Forney 2000, Barlow et al. 2009, Becker et al. 2010, Forney et al. 2012), predictions based on novel data sets (Barlow et al. 2009, Becker et al. 2012, Forney et al. 2012, 2015, Becker et al. 2014), and expert opinion (Barlow et al. 2009, Forney et al. 2012).

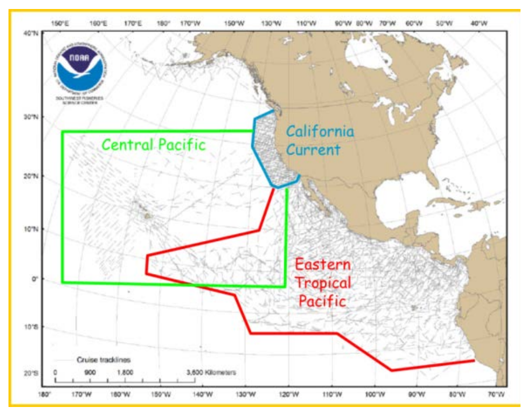

Figure A. Transect coverage for surveys conducted by SWFSC between 1986 and 2006 in three broad study areas in the eastern North Pacific.

All of the above models were developed within a generalized additive modeling framework (Hastie & Tibshirani 1990) at ecosystem-dependent scales ranging from 2 km to 120 km (*e.g.*, Forney 2000, 2012, Ferguson et al. 2006, Redfern et al. 2008, Becker et al. 2010, 2012, 2016). Dynamic environmental covariates used in the models included remotely sensed data (*e.g.*, sea surface temperature [SST] and its standard deviation, chlorophyll concentration [CHL], sea surface height [SSH], and SSH root-mean-square variation), and data collected *in situ* during the line-transect surveys (SST, CHL, sea surface salinity [SSS], mixed layer depth [MLD], and thermocline depth and strength). More recently, dynamic variables from ocean models have been used as potential predictors in the habitat models, including SST and its standard deviation, SSS, MLD, SSH and the standard deviation of SSH (Becker et al. 2016). The habitat predictors included in these models all serve as proxies for unmeasured underlying ecological processes linking cetaceans to their prey.

Models have successfully captured variability in cetacean density and distribution at seasonal and interannual time scales (*e.g.* Fig. B, Forney et al. 2012, Becker et al. 2014, 2016). While the multi-year average models provide a valuable tool for managers (*e.g.*, Redfern et al. 2013), they only reflect historical data and the variation therein and do not take into account current or future conditions. Given emerging emphases on dynamic ocean management (*e.g.*, Hobday et al. 2014, Maxwell et al. 2015) and the need for addressing species distribution relative to climate change, habitat predictors from ocean circulation models offer opportunities for dynamic predictions. Becker et al. (2012) demonstrated that advanced satellite data and forecasts from ocean models allow "nowcasts" of marine mammal distributions on time scales of days to weeks and forecasts on time scales of 3-4 months. While the SWFSC studies have not yet directly addressed climate change, they have developed robust methods and extensively validated habitat-based density models for cetaceans, primarily in the CCE. A recent study demonstrated that ocean circulation models provide robust predictive models of cetacean distributions, showing promise for future predictions of marine mammal distributions in a changing climate (Becker et al. 2016). However, the models rely on proxy variables (*i.e.*, they are not mechanism-driven models), and future forecasts can fail if the proxy relationships change. Future steps require additional model validation, particularly at different spatial resolutions and longer temporal scales.

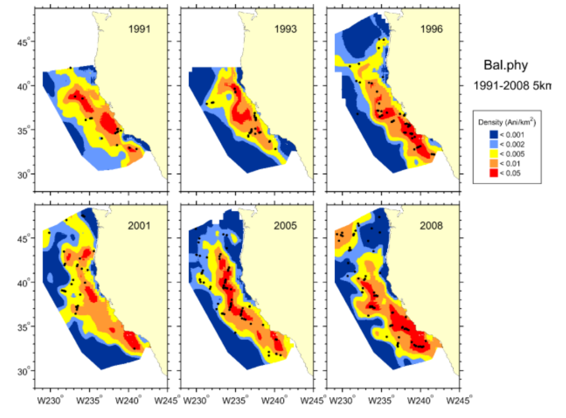

Figure B. Model-based estimates of fin whale summer/fall density (animals/km^{-2}) and distribution for six different years, 1991-2008, in the California Current Ecosystem. Black dots show actual sighting locations during ship surveys conducted in each year. (Details provided in Becker et al. 2016).

Data Types, Data Evaluation, and Data Limitations

In this section, we describe a conceptual framework and rationale for evaluating data available for incorporating into forecast modeling. We define data broadly to include in-situ observations, remotely-sensed data, model output, and proxies, among others.

Data used in models are diverse (*e.g.*, physical, biological, biogeochemical) and the amount of data available to address a particular question may vary. Situations can be characterized as data or model rich/poor. Science strives to move from data, model, and prediction poor scenarios to data, model, and prediction rich conditions (Fig. 4). In any modeling exercise, data limitations and gaps should be identified and considered when determining appropriate modeling approaches. As discussed above, even some data poor and model poor approaches can be valuable and may serve management needs in specific situations (see section on "Types of Models, and Selecting Appropriate Models" above). And, as also previously indicated in this report, expanding collaborators and disciplines engaged in the effort and seeking input from multidisciplinary teams can be vital to building a robust forecast modeling endeavor.

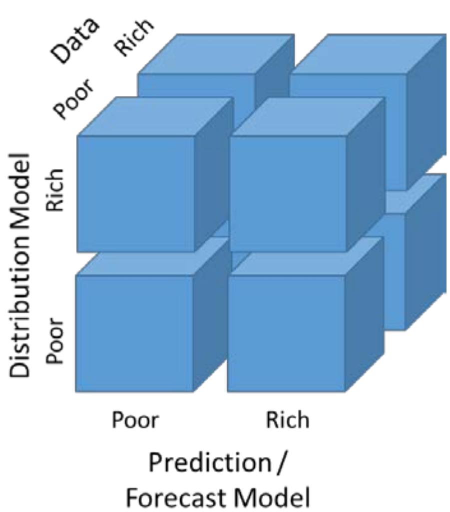

Figure 4. Model and data characteristics and their relationship to model prediction and forecasting capabilities. The goal of science is to move from data, model and prediction poor scenarios to data, model and prediction rich scenarios.

Physical Data as Proxies

Forecasting future species distributions requires the use of habitat variables and ecological processes that can be suitably and confidently projected into the future. Mechanistic processes within a food web or ecosystem can be difficult to measure and model and biological parameters or environmental data may be few or unavailable. Highly detailed models will be of limited utility for future projections if the model variables cannot be reliably projected in ways that anticipate future climate change. These challenges have led modelers to search for simpler means, or proxies, to approximate certain processes. Physical oceanographic data are more readily observed and modeled than ecological, physiological, and food web processes and can serve as useful proxies for those processes.

Physical data are obtained from a variety of sources including observing stations, ship surveys, drifters, and satellites. The breadth of data sources results in a variety of observed temporal and spatial resolutions and a range of confidence levels, but generally physical data can be measured with finer resolution and greater confidence than exist for the biological/ecological data. Observational bases for physical data are more comprehensive than for ecosystems, and physical data can also be modeled more easily than biological data, with several models providing physical proxy projections that can be used as inputs for biological models (*e.g.*, Stock et al. 2015, Saba et al. 2016).

Physical parameters discussed during presentations at the workshop included:

- Chlorophyll concentration
- Distance to mainland
- Distance to shelf or isobath
- Mixed layer depth
- Salinity
- Sea floor aspect
- Sea floor slope
- Sea ice concentration
- Sea surface height
- Sea surface temperature
- Snow depth
- Water depth

Physical variables form the basis for correlative envelope models (discussed above in the section on “Types of Models and Selecting Appropriate Models) that establish a statistical relationship between a modeled species and a variable or set of variables in its physical environment. Species distribution modeling assumes those relationships will continue into the future *(i.e.*, relationships remain stationary) and distributions can be projected into novel conditions (*e.g*., extrapolation). However, there may be no assurances that the relationship will hold under new or changing conditions or that the relationship is causative.

Modeling with Proxy Variables

Physical proxies tend to accurately represent linkages to the physical environment for species feeding at low trophic levels. Therefore, well-documented relationships with specific parameters (*e.g*., phytoplankton) can be approximated using physical parameters. Many fish species exhibit tight linkages to physical oceanographic features because they are ectothermic and may be limited to particular water masses or temperatures. Some marine mammal species have some degree of flexibility and may be able to tolerate a wider range of temperature regimes than many fish or invertebrate species. Nonetheless, some species such as blue whales (*Balaenoptera musculus*) have shown tight coupling to certain physical oceanographic features (Fiedler et al. 1998, Moore et al. 2002), likely because they feed on low trophic level organisms that are themselves tightly linked to the physical environment. Other marine mammal species likely exhibit similar relationships, *e.g*., bowhead (*Balaena mysticetus*) (George et al. 2015) and right whales and thus the use of proxy variables may be appropriate. Modelers can expect far less success with dependence on proxy variables with higher trophic level predators such as sperm whales (*Physeter macrocephalus*) or small odontocete species that are prey generalists, because such efforts are complicated by multiple trophic level interactions and the subject organism's prey may be only indirectly linked to the physical environment.

A given projection model may not specifically include chlorophyll concentration, for example, but this feature might serve as a proxy for higher trophic level relationships in modeling future conditions. Similarly, bottom water temperatures as related to animal occurrence may not be well captured in a forecasting model, but statistical downscaling can be used to develop an indicator of bottom water temperature in the future. The same holds true for biological parameters which may not be available for the species of interest, but information from a closely related species or various environmental factors could be used as a proxy instead.

In some cases, it may be worthwhile to develop more "naïve" models that use proxy variables that are both currently available and can be incorporated into future projections, as opposed to the use of more conceptually "correct" variables (*e.g.*, environmental variables on a small spatial scale) that are not available for future projections. An alternative to using proxy variables directly is to identify statistical relationships between proxy variables and the variables of interest. For example, Spencer et al. (*In press*) found a relationship between the distribution of arrowtooth flounder (*Atheresthes stomias*) in the eastern Bering Sea and the "cold pool" (bottom water $\leq$ 2 °C). Projections of the future size of the cold pool were obtained from a statistical relationship between cold pool area (the variable of interest) and sea level pressure and sea ice extent (the proxies), which were available from global climate models. Thus, the location and extent of these cold water features provided a proxy by which the expected distribution of the flounder might be forecast.

Beyond Physical Data – Modeling with Tractable and Intractable Features

A range of factors other than the physical environment will affect marine mammal modeling efforts, including trophic interactions (distribution of predators, competitors, and prey), disease and parasites, and anthropogenic factors (*e.g.*, disturbance, fishing pressure, shipping). The possible effect of these factors might be broadly characterized by running a range of simulations of their impact on potential future distributions. Some factors may be tractable within current modeling approaches, and they might be included in the initial baseline model. In other words, some generalizations can be made for all marine mammals (*e.g.*, long generation times may make behavioral plasticity more important than evolutionary responses over the short term), while other features may be species specific (*e.g.*, degree of site fidelity to haul-out sites or migration routes).

In contrast, some factors (*e.g*., species plasticity, prey switching, resilience, evolutionary effects (Forcada et al. 2006), behavioral changes, and site fidelity) are difficult to model and might significantly alter model results. In particular, the ability of marine mammals to alter their behavior or food sources can act as a buffer to measurable climate-change induced changes, and can delay any adverse effects, or mask them until critical thresholds are reached. Ignoring such behavioral effects in models can result in overly pessimistic projections, with effects predicted as occurring too rapidly. At the same time, models may provide a longer term, more visionary picture that uncovers larger trends or underlying directional processes, which may be otherwise masked in observations of near-term marine mammal behavior. Such a mismatch between projections and reality can undermine faith in the model projections.

In addition, "surprise" or stochastic events cannot be forecast. Variables such as the potential for a very warm year or a year with large-scale sea ice loss may adversely affect model outputs. These might be modeled generally, but the precise timing and magnitude may not be predictable. Therefore, the key is to identify and incorporate the well-understood variables during initial model development and then include those that are more intractable to provide a selection of plausible alternative responses.

Exemplar Species/Population(s) for Assessing Modeling Methodologies

One of the workshop's principal objectives was to "identify one or more exemplar species/population(s) for assessing [modeling] methodologies or metrics." We approached this by first discussing features of various marine mammal populations, complexes of species, or regions that might represent good candidates for further study. The goal was to identify populations (*e.g.*, data rich, highly vulnerable) most suitable for proof-of-concept forecast modeling, and conversely those that might have a somewhat lower priority (*e.g.*, high abundance or low management needs).

The workshop concluded that species or populations exposed to existing threats and vulnerable to large scale ecosystem shifts, that represent a current management priority, or occur in rapidly changing ecosystems should receive most emphasis in consideration of next-generation forecasting studies. In addition, selection of marine mammal populations for modeling studies might be based on a balance of interacting (or competing) factors. For example, it may be of relatively limited added value to devote resources to a population that is abundant and increasing in size and/or of relatively low management need priority, and for which modeling capabilities may be limited (*e.g.*, sperm whales) (Fig. 5). Conversely, greater emphasis might be placed on species where, in combination, both modeling capability is high and the management need is great (*e.g.*, ice or Hawaiian monk seals).

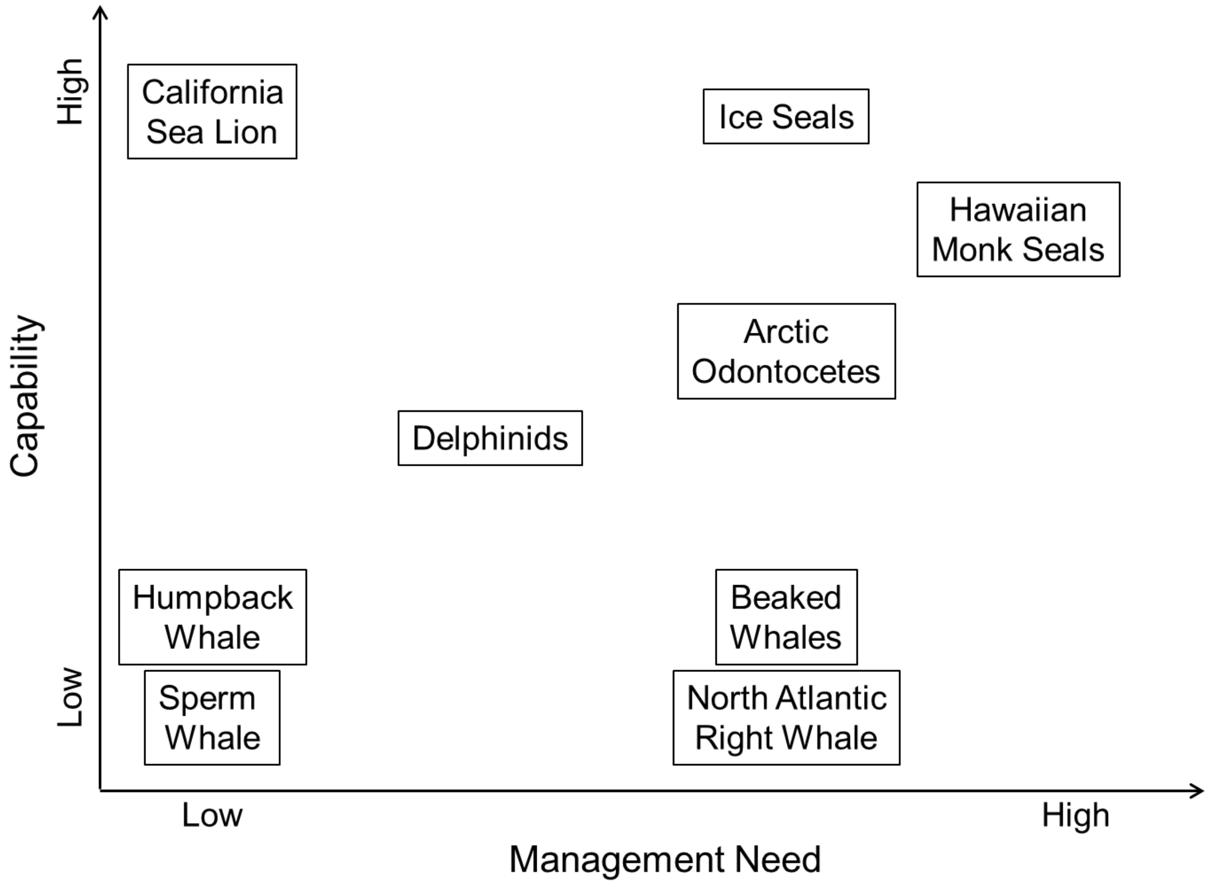

Figure 5. The range of increasing modeling capability and management need for some illustrative marine mammal populations. Species and their relative positions are provided for illustration purposes and may not indicate an official agency prioritization.

Highly Vulnerable Species or Populations

Projecting the effects of climate change on highly vulnerable populations, particularly in cases where known threats are already occurring, should be a high priority. Some marine mammal populations are experiencing known or suspected population declines or slow population growth (*e.g*., vaquita (*Phocoena sinus*), Cook Inlet beluga whale (*Delphinapterus leucas*), Hawaiian monk seal). Species or populations with limited ranges, specialized diets, or similarly limiting ecological features may be particularly vulnerable to a changing climate. Such species may also be exposed to additional known anthropogenic impacts (*e.g*., incidental by-catch in commercial or artisanal fisheries) or habitat perturbations, thereby increasing their susceptibility to ecosystem changes should they occur within their ranges. Future effects of climate change on these and other vulnerable populations are not known, but the possibility of such effects should be evaluated.

A recent workshop and related follow-up discussions focused specifically on identifying which protected marine vertebrates (*i.e*., pinnipeds, cetaceans, and turtles) were likely to be vulnerable to climate change, and identifying the attributes that make them vulnerable (NOAA, *in draft*). To the extent possible, those marine mammal populations deemed most at risk as a result of these vulnerability assessment efforts should receive high priority when considering future forecasting exercises. The workshop we describe here avoided duplication of that discussion – but the findings of that work, when completed, should be factored into decisions regarding next step modeling studies.

Management Priority

As indicated in the "Resource Management Needs and Modeling Horizons" section above, a number of depleted or recovering populations should be afforded high priority when considering climate change-related modeling work. Among these are ESA-listed marine mammal species.

By way of example, NMFS recently identified three "Species in the Spotlight" marine mammal populations -- those most at risk of extinction in the near future: Cook Inlet (Alaska) beluga whales, Hawaiian monk seals, and southern resident killer whales (*Orcinus orca*). These populations are likely candidates for modeling studies because they fit a number of criteria identified here (*i.e*., small population sizes, exposure to known threats, and relatively data rich). In any case, government-fostered and funded forecasting research on climate change impacts on marine mammals might focus first and foremost on those populations with the greatest management needs (Fig. 5).

Populations Inhabiting Rapidly Changing Environments

Plans for predictive modeling efforts might also include species that are residents or seasonal migrants in high latitudes. In fact, forecasting work has already been done on polar bears (*Ursus maritimus*), ice seals, and walruses (*Odobenus rosmarus*) in the context of developing biological opinions for proposed ESA listings (Jay et al. 2011). High-latitude regions are exhibiting more rapid climate change than low-latitude regions (*e.g*., Doney et al. 2012, MMC 2012, Thomas et al. 2015). Marine mammal populations (and their prey) occurring in these locations may exhibit changes in relative abundance and possible range expansions or contractions, or other ecological disruptions sooner than ecosystems at lower latitudes (*e.g*., Laidre et al. 2008, Moore and Huntington 2008, Gilg et al. 2012). Rapid shifts in occurrence or availability of key prey species in these areas may likewise be expected in the foreseeable future (Thomas et al. 2015). Perhaps most important among these are ice-obligate species, particularly when ice provides a platform for raising young (*e.g*., ringed seal (*Phoca hispida*) pupping lairs) (NOAA 2012), a source of prey (*e.g*., polar bears), or where key prey species are closely or directly linked to ice (*e.g*., Antarctic fur seals (*Arctocephalus gazella*)) (Forcada et al. 2008).

In addition, indications regarding the magnitude of climate change are themselves evolving. As an example, a recent high-resolution climate model has indicated that the northeast U.S. shelf and specifically the Gulf of Maine may warm about two times faster than previously thought

(Saba et al. 2015). This enhanced warming results from a climate-forced change in circulation which is not simulated in models with lower resolution. Based on new information about the magnitude of change in certain locations, or in similar situations where model capabilities are improving, evaluation of the updated impact to marine mammals in waters off New England and eastern Canada should be a priority.

Data-rich Populations

Much more is known about the ecology of and the drivers of distribution and occurrence for some populations and in some locations (*e.g.*, blue whales (Fiedler et al. 1998, Croll et al. 2005) and North Atlantic right whales (Baumgartner et al. 2003)) than for others. As indicated elsewhere in this report, in cases where abundant data exist on marine mammal occurrence, and the environmental features (prey, in particular) linked to seasonal and annual occurrence, forecasting will be more robust and uncertainties fewer than for data-poor populations. Therefore, modeling data-rich populations is highlighted given the relative precision in predictive capabilities is high. These subjects are of particular importance as providing testing grounds to identify and test methods and parameters which might then be used for less tractable species and areas. In addition, these studies are cost-effective inasmuch as data already exist for these populations.

Species Complexes

To maximize use of limited (analytical) resources, consideration should be given to systems where distributional shifts of multiple species, even at multiple trophic levels, could be modeled (for a discussion, see section "Analytical Tools: Selecting Appropriate Models" above). If the ecology of several species, particularly as they are interrelated (*e.g.*, predator-prey relationships), is relatively well-known, managers may benefit from predictions of expected changes occurring in suites of species in a given system.

Given the level of effort that has been devoted to characterizing their physical and biological components, as well as their marine mammal populations, the California Current and Bering Sea ecosystems are particularly important areas for such modeling efforts. Regional marine mammal species complexes have been the subject of predictive modeling studies is in the California Current (Redfern et al. 2013, Becker et al. 2012, 2014, 2016, Dransfield et al. 2014). Strong consideration should be given to continuing these studies because adequate environmental and species distribution data already exist, linkages between species occurrence and their environmental drivers have been studied, and these systems are relatively well-known and have been well-modeled. Inasmuch as these are ongoing studies, they are a more cost-effective (*i.e.*, relatively less commitment of resources up front) means of ongoing proof-of-concept and model validation than situations where data collection and model development/evaluation might require a costly initiation of research. They provide a means to capitalize on interdisciplinary work already conducted on other taxa and will maximize use of available resources.

Confounding Factors for Species Selection

As noted above, the capacity for a species or individual to accommodate changing ecosystems may depend in the short term on aspects of its behavior and ecology (Trathan et al. 2007). For example, species that feed on diverse prey types (*e.g*., bottlenose dolphins, humpback whales), with relatively flexible phenologies, or are not dependent on a specific substrate or location may experience relatively fewer impacts from changing ecosystems than those that are reliant on a particular prey (*e.g*., crabeater seal (*Lobodon carcinophaga),* North Atlantic right whales), habitat type, or location. Therefore, those species with relatively narrow behavioral or phenotypic plasticity might also receive priority in future modeling studies.

Climate change impacts may have disruptive influences at multiple trophic levels (Doney et al. 2012, Sydeman et al. 2015). Complex food webs may experience trophic cascades and food web disruptions at drastically different scales and rates than those with only primary or secondary trophic interactions. In addition, some commercially valuable mid-trophic level fish species may be exploited by fisheries – a situation with added ramifications for marine mammal species that prey on the same resource (Forcada et al. 2012). Top-level predators such as killer whales, polar bears, and leopard seals (*Hydrurga leptonyx*) may be impacted differently than those preying at lower trophic levels, such as right whales and walruses. Therefore, systems with relatively few trophic connections (*e.g*., those involving some baleen whale species) may be relatively simpler to model (where data are available) than those with complex food webs.

Summary – Exemplar Species

In sum, next-generation predictive modeling exercises might reasonably focus first on species/populations a) that are depleted or currently undergoing declines in abundance; b) that represent high management priority because they are exposed to multiple anthropogenic threats; c) for which aspects of their ecology are already quantified; or d) that occur in high latitude species.

Next Steps

Suggested Research and Study Needs and Policy Considerations

Given workshop discussions and the findings described above, a number of short- and long-terms actions might be pursued.

Workshop Follow-up

By way of follow-up, agency leadership might consider constituting groups (particularly interdisciplinary groups), encouraging additional studies or data collection, engaging in advance budget planning to foster further work, and undertaking related actions subsequent to this workshop in the following areas.

Manager-Scientist Interface

Ideally, processes for marine resource managers to effectively communicate research and analytical needs to researchers should be developed and/or improved. Fora for researchers to communicate to managers the strengths and weaknesses inherent in modeling studies, the importance of uncertainties in modeling exercises, and to help provide an awareness about assumptions and values that contributed to model outputs are also needed.

Methods to encourage this dialog might include establishing a working group or organizing a follow-on workshop to address specific issues identified here. Goals for a workshop might include identifying prioritized lists of species (or populations), species complexes, or regions for specific modeling studies. These might be based, at least initially, on the criteria discussed above in the "Exemplar species/population(s) for assessing modeling methodologies" section and in conjunction with marine protected species vulnerability assessment work. These discussions should also include processes to identify specific modeling needs as changes in marine mammal distribution expose these animals to impacts from particular human activities (*e.g.*, renewable energy lease sales) or as the need arises to develop new management measures (*e.g.*, establishing critical habitat). It may also include identifying initial modeling trials involving both species/populations readily modeled as well as those representing greater challenges and uncertainties, which incorporate testing and validation of each. In this regard, attention might also be paid to the collaborations that support successful modeling efforts and consideration given to how to facilitate such teams (see below).

Forecasting Distributions of Illustrative Marine Mammal Populations – Conduct Modeling Case Studies

The workshop identified a number of marine mammal populations that, for various reasons (described in general terms in the "Exemplar Species/population(s) for Assessing Modeling Methodologies" section above), might serve well as case studies to project future distributions and illustrate the state-of-play for current modeling capabilities. Consideration should be given to advancing these and related studies. These studies might focus intensive work on a few species (or suite of species) one by one – an approach that might then inform the modeling of other species. By way of analogy, "Potential Consequences of Disturbance" (PCoD) models (Harwood et al. 2014) have been used for in-depth study of individual marine mammal populations (*e.g.*, Costa et al. 2016).

Model Validation

Modeling is an iterative process. Therefore, as a general matter, and as a follow-up to studies described above, it is essential to plan for the testing or validation of these forecasts as additional data become available and as analytical approaches are refined (Fig. 3). Because every model contains some level of uncertainty, the workshop concluded that efforts are needed to continually refine models to diminish uncertainty to the extent possible. Therefore, processes should be developed for identifying future analytical work that includes systematic feedback with an emphasis on hypotheses testing and model validation using, for example, species-habitat models as well as hybrid (mechanistic and correlative) models to predict spatial distributions, and continually applying new information as it becomes available. These steps will improve overall modeling rigor and resolution and should be regarded as an ongoing exercise.

Ongoing Data Collection

As noted in the paragraph immediately above, predictive models are improved as new data are incorporated. Therefore, plans should be made, where practicable, to collect and make available additional marine mammal occurrence and environmental correlate data in locations and involving species where critical needs exist or where modeling studies are underway.

A central message from the workshop was that marine mammals may respond more to the distribution of their prey than to the environment. Therefore, studies should be fostered that provide increased observations and improved modeling of prey resources as drivers of marine mammal distribution (as well as the physical and biological features that dictate prey occurrence). In addition, although marine mammals are distributed broadly, including in habitats well outside the continental shelf, most monitoring programs are largely coastal in focus. As a result, it may be difficult to validate models and to detect changes in distribution and regional abundance of many species. Consideration should be given to developing (or prioritizing) monitoring networks that incorporate additional assets outside areas where marine mammals are traditionally studied. Passive acoustic technologies, including, for example, autonomous underwater vehicles and underwater gliders equipped with marine mammal acoustic detection capabilities – are technologies well-suited for this purpose, both because they can reach remote areas, and because they can collect important physical and oceanographic data along with biological data.

Time Scales for Modeling

For many marine mammal populations, “nowcasts” and projections in the short term (months to years) can be made with relative certainty, but projections in the longer term (decades to centuries) have less certainty. Many management needs are on relatively long time scales – so, uncertainties inherent to these scales are likely to remain a challenge for the foreseeable future. Therefore, intra- and inter-agency, multidisciplinary working groups might be established to design studies to address the level of uncertainties in projections on mid- an long-time scales, to identify specific ways in which next-generation marine mammal modeling studies might be refined, and determine ways in which long-time scale uncertainties can be addressed in management decisions.

The Value of Inter-/Multi-disciplinary Teams

A common theme among the presentations and in subsequent discussions was the importance of engaging multiple disciplines when establishing a project team. Including expertise in disciplines such as climate science, ecology, physical oceanography, statistics, marine resource management, and social science strengthens the separate components of the project to improve the overall utility and confidence in the project outputs. Project leads and research scientists should consider including expertise from related disciplines when planning modeling projects. In addition, seeking multi-disciplinary expertise should also be a practice fostered by agency leadership when modeling projects are under development.

Fiscal Planning

The influence of climate change on oceanographic processes and living marine resources will present challenges for managers into the foreseeable future. Accordingly, relevant agencies should begin now to engage in long-term fiscal planning to equip scientists and managers with the tools and resources needed to address these challenges. This should include planning for new and enhanced data collection and enhancing ongoing studies, and model development and refinement studies, particularly in settings where conservation/management needs are greatest.

Literature Cited

Angliss RP, Silber GK and Merrick R. 2002. Report of a workshop on developing recovery criteria for large whale species. US Department of Commerce, NOAA Technical Memorandum, NMFS-OPR-21. 36p.

Angunuzzi AA and Buckland ST. 1994. Relative abundance of dolphins associated with tuna in the eastern Pacific Ocean: Analysis of 1992 data. Report of the International Whaling Commission. 44:361-366.

Barlow J, Ferguson MC, Becker EA, Redfern JV, Forney KA, Vilchis IL, Fiedler PC, Gerrodette T and Ballance LT. 2009. Predictive modeling of cetacean densities in the Eastern Pacific Ocean. US Department of Commerce, NOAA Technical Memorandum, NOAA-TM-NMFS-SWFSC-444. 229p.

Baumgartner MF, Cole TVN, Clapham PJ and Mate BR. 2003. North Atlantic right whale habitat in the lower Bay of Fundy and on the SW Scotian Shelf during 1999–2001. *Marine Ecology Progress Series*. 264:137-154. doi: 10.3354/meps264137.

Baumgartner MF and Mate BR. 2005. Summer and fall habitat of North Atlantic right whales (*Eubalaena glacialis*) inferred from satellite telemetry. *Canadian Journal of Fisheries and Aquatic Sciences* 62:527-543.

Becker EA, Forney KA, Ferguson MC, Foley DG, Smith RC, Barlow J and Redfern JV. 2010. Comparing California Current cetacean-habitat models developed using *in situ* and remotely sensed sea surface temperature data. *Marine Ecology Progress Series*. 413:163-183. doi: 10.3354/meps08696.

Becker EA, Foley DG, Forney KA, Barlow J, Redfern JV and Gentemann CL. 2012. Forecasting cetacean abundance patterns to enhance management decisions. *Endangered Species Research.*16:97-112. doi: 103354/esr00390.

Becker EA, Forney KA, Foley DG, Smith RC, Moore TJ and Barlow J. 2014. Predicting seasonal density patterns of California cetaceans based on habitat models. *Endangered Species Research.* 23:1-22. doi: 10.3354/esr00548.

Becker EA, Forney KA, Fiedler PC, Barlow J, Edwards CA, Moore AM and Redfern JV. 2016. Moving towards dynamic ocean management: how well do modeled ocean products predict species distributions? *Remote Sensing*. 8:149-174. doi: 10.3390/rs8020149.

Best BD, Halpin PN, Read AJ, Fujioka, Good CP, LaBreque EA, Schick RS, Roberts JJ, Hazen LJ, Qian SS, Palka DL, Garrison LP and McLellan WA. 2012. Online cetacean habitat modeling system for the US east coast and Gulf of Mexico. *Endangered Species Research*. 18:1-15. doi: 10.3354/esr00430.

Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R and Pauly D. 2009. Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries*. 10:235–251. doi: 10.1111/j.1467-2979.2008.00315.x.

Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R, Zeller D and Pauly D. 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*. 16:24-35. doi: 10.1111/j.1365-2486.2009.01995.x.

Cheung WW, Frölicher TL, Asch RG, Jones MC, Pinsky ML, Reygondeau G, Rodgers KB, Rykaczewski RR, Sarmiento JL, Stock C and Watson JR. 2016. Building confidence in projections of the responses of living marine resources to climate change. *ICES Journal of Marine Science*. 14p. doi: 10.1093/icesjms/fsv250.

Clarke J, Stafford K, Moore SE, Rone B, Aerts L and Crance J. 2013. Subarctic cetaceans in the southern Chukchi Sea: Evidence of recovery or response to a changing ecosystem. *Oceanography*. 26:136–149. http://dx.doi.org/10.5670/oceanog.2013.81.

Costa DP, Schwarz L, Robinson P, Schick RS, Morris PA, Condit R, Crocker DE, Kilpatrick AM. 2016. A bioenergetics approach to understanding the population consequences of disturbance: Elephant seals as a model system. *Advances in Experimental Medicine and Biology*. 875:161-9. doi: 10.1007/978-1-4939-2981-8_19.

Cribb N, Miller C, and Seuront L. 2015. Towards a standardized approach of cetacean habitat: past achievements and future directions. *Open Journal of Marine Science*, 5: 335-357. http://dx.doi.org/10.4236/ojms.2015.53028.

Croll DA, Marinovic BB, Benson S, Chavez FP, Black N, Ternullo R and Tershy BR. 2005. From wind to whales: Trophic links in a coastal upwelling system. *Marine Ecology Progress Series*. 289:117-130. doi: 10.3354/meps289117.

Cuddington K, Fortin MJ, Gerber LR, Hastings A, Liebhold A, O'Connor M, and Ray C. 2013. Process-based models are required to manage ecological systems in a changing world. *Ecosphere.* 4:20. http://dx.doi.org/10.1890/ES12-00178.1

Doney SC, Ruckelshaus M, Duffy JE, Barry JP, Chan F, English CA, Galindo HM, Grebmeier JB, Hollowed JB, Knowlton N, Polovina J, Rabalais NN, Sydeman WJ and Talley LD. 2012. Climate change impacts on marine ecosystems. *Annual Review of Marine Science*. 4:11–37. doi: 10.1146/annurev-marine-041911-111611.

Dransfield A, Hines E, McGowan J, Holzman B, Nur N, Elliott M, Howar J and Jahncke J. 2014. Where the whales are: Using habitat modeling to support changes in shipping regulations within National Marine Sanctuaries in Central California. *Endangered Species Research*. 26:39–57. doi: 10.3354/esr00627.

Dunn DC, Maxwell SM, Boustany AM and Halpin PN. 2016. Dynamic ocean management increases the efficiency and efficacy of fisheries management. *Proceedings of the National Academy of Sciences of the United States of America*. 113: 668-673. doi: 10.1073/pnas.1513626113.

Ferguson MC, Barlow J, Fiedler P, Reilly SB and Gerrodette T. 2006. Spatial models of delphinid (family Delphinidae) encounter rate and group size in the eastern tropical Pacific Ocean. *Ecological Modeling*. 193:645-662. doi:10.1016/j.ecolmodel.2005.10.034.

Fiedler PC, Reilly SB, Hewitt RP, Demer D, Philbrick VA, Smith S, Armstrong W, Croll DA, Tershy BR and Mate BR. 1998. Blue whale habitat and prey in the California Channel Islands. *Deep-Sea Research II*. 45: 1781-1801. doi:10.1016/S0967-0645(98)80017-9.

Forcada J, Trathan PN, Reid K, Murphy EJ and Croxall JP. 2006. Contrasting population changes in sympatric penguin species in association with climate warming. *Global Change Biology*. 12:411-423. doi: 10.1111/j.1365-2486.2006.01108.x.

Forcada J, Trathan P N, Murphy E J. 2008. Life history buffering in Antarctic mammals and birds against changing patterns of climate and environmental variation. *Global Change Biology*. 14:2473-2488. doi: 10.1111/j.1365-2486.2008.01678.x.

Forcada J, Trathan PN, Boveng PL, Boyd IL,Burns JM,Costa DP, Fedak M, Rogers TL, Southwell CJ. 2012. Responses of Antarctic pack-ice seals to environmental change and increasing krill fishing. *Biological Conservation*. 149:40-60. http://dx.doi.org/10.1016/j.biocon.2012.02.002

Forney KA. 2000. Environmental models of cetacean abundance: reducing uncertainty in population trends. *Conservation Biology*. 14:1271-1286. doi: 10.1046/j.1523-1739.2000.99412.x.

Forney KA, Ferguson MC, Becker EA, Fiedler PC, Redfern JV, Barlow J, Vilchis IL and Ballance LT. 2012. Habitat-based spatial models of cetacean density in the eastern Pacific Ocean. *Endangered Species Research*. 16:113-133. doi: 10.3354/esr00393.

Forney KA, Becker EA, Foley DG, Barlow J and Oleson EM. 2015. Habitat-based models of cetacean density and distribution in the central North Pacific. *Endangered Species Research*. 27:1-20. doi: 10.3354/esr00632.

George JC, Druckenmiller, ML, Laidre KL, Suydam R, and Brian Person. B. 2015. Bowhead whale body condition and links to summer sea ice and upwelling in the Beaufort Sea. *Progress in Oceanography*. 136:250–262.

Gilg O, Kovacs KM, Aars J, Fort J, Gauthier G, Grémillet D, Ims RA, Meltofte H, Moreau J, Post E, Schmidt NM, Yannic G and Bollache L. 2012. Climate change and the ecology and evolution of Arctic vertebrates. *Annals of the New York Academy of Sciences*. 1249:166–190. doi: 10.1111/j.1749-6632.2011.06412.x.

Gilles A, Adler S, Kaschner K, Scheidat and Siebert U. 2011. Modelling harbor porpoise seasonal density as a function of the German Bight environment: Implications for management. *Endangered Species Research*. 14:157–169. doi: 10.3354/esr00344.

Gregr EJ, Baumgartner MF, Laidre KL, Palacios DM. 2013. Marine mammal habitat models come of age: The emergence of ecological and management relevance. *Endangered Species Research*. 22:205-212.

Griffis RB, Feldman RL, Beller-Simms NK, Osgood KE and Cyr N (eds). 2008. Incorporating climate change into NOAA's stewardship responsibilities for living marine resources and coastal ecosystems: a strategy for progress. US Department of Commerce, NOAA Technical Memorandum. NMFS-F/SPO-95. 97p.

Gutt J, Zurell D, Bracegridle DJ, Cheung W, Clark MS, Convey P, Danis B, David B, De Broyer C, di Prisco G, Griffiths H, Laffont R, Peck LS, Pierrat B, Riddle MJ, Saucède T, Turner J, Verde C, Wang Z and Grimm V. 2012. The use of correlative and dynamic species distribution modelling for ecological predictions in the Antarctic: a cross-disciplinary concept. *Polar Research*. 31:11091. http://dx.doi.org/10.3402/polar.v31i0.11091.

Hansen LJ. 1990. California coastal bottlenose dolphins. *In*: Leatherwood S and Reeves RR (eds), *The Bottlenose Dolphin*, Academic Press, San Diego, CA. 403-420p.

Hare JA, Wuenschel MJ and Kimball ME. 2012a. Projecting range limits with coupled thermal tolerance-climate change models: An example based on gray snapper (*Lutjanus griseus*) along the U.S. East Coast. *PLoS ONE*. 7(12): e52294. doi:10.1371/journal.pone.0052294.

Hare JA, Manderson JP, Nye JA, Alexander MA, Auster PJ, Borggaard DL, Capotondi AM, Damon-Randall KB, Heupel E, Mateo I, O'Brien L, Richardson DE, Stock CA and Biegel ST. 2012b. Cusk (*Brosme brosme*) and climate change: assessing the threat to a candidate marine fish species under the US Endangered Species Act. *ICES Journal of Marine Science*. 69:1753–1768. doi: 10.1093/icesjms/fss160.

Hare JA, Morrison WE, Nelson MW, Stachura MM, Teeters EJ, Griffis RB, Alexander MA, Scott JD, Alade L, Bell RJ, Chute AS, Curti KL, Curtis TH, Kircheis D, Kocik JF, Lucey SM, McCandless CT, Milke LM, Richardson DE, Robillard E, Walsh HJ, McManus MC, Marancik KE and Griswold CA. 2016. A vulnerability assessment of fish and invertebrates to climate change on the Northeast U.S. Continental Shelf. *PLoS ONE*. 11(2): e0146756. doi:10.1371/journal.pone.0146756.

Harwood J, King S, Schick R, Donovan C, Booth C. 2014. A protocol for implementing the interim population consequences of disturbance (PCoD) approach: Quantifying and assessing the effects of UK offshore renewable energy developmenets on marine mammal populations: Report number SMRUL-TCE-2013-014. *Scottish Journal of Marine Freshwater Science*. 5:2.

Hastie TJ and Tibshirani RJ. 1990. Generalized additive models. Chapman and Hall, New York, NY.

Hazen EL, Jorgensen S, Rykaczewski RR, Bograd SJ, Foley DG, Jonsen ID, Shaffer SA, Dunne JP, Costa DP, Crowder LB and Block BA. 2013. Predicted habitat shifts of Pacific top predators in a changing climate. *Nature Climate Change*. 3:234-238. doi:10.1038/nclimate1686.

Heyning JE and Perrin WF. 1994. Evidence for two species of common dolphins (Genus Delphinus) from the eastern North Pacific. Contribution in Science, Natural History Museum of Los Angeles County, No 442. Allen Press, Lawrence, KS.

Hezel, PJ, Zhang X, Bitz CM, Kelly BP, and Massonnet F. 2012. Projected decline in spring snow depth on Arctic sea ice caused by progressively later autumn open ocean freeze-up this century. *Geophysical Research Letters*. 39:L17505. doi: 10.1029/2012GL052794.

Hobday AJ, Hartog JR, Spillman CM and Alves O. 2011. Seasonal forecasting of tuna habitat for dynamic spatial management. *Canadian Journal of Fisheries and Aquatic Sciences*. 68:898–911. doi: 10.1139/f2011-031.

Hobday AJ, Maxwell SM, Forgie J, McDonald J, Darby M, Seto K, Bailey H, Bograd SJ, Briscoe DK, Costa DP, Crowder LB, Dunn DC, Fossette S, Halpin PN, Hartog JR, Hazen EL, Lascelles BG, Lewison RL, Poulos G and Powers A. 2014. Dynamic ocean management: Integrating scientific and technological capacity with law, policy and management*. Stanford Environmental Law Journal*. 33:125-165.

Hutchinson GE. 1957. Concluding remarks. *Cold Spring Harbor Symposium on Quantitative Biology*. 22:415-427. doi:10.1101/SQB.1957.022.01.039

Hyrenbach KD, Forney KA and Dayton PK. 2000. Marine protected areas and ocean basin management. *Aquatic Conservation: Marine and Freshwater Ecosystems*. 10:437-458. doi: 10.1002/1099-0755(200011/12)10:6<437.

Hyrenbach KD, Keiper C, Allen SG, Anderson DJ and Ainley DG. 2006. Use of national marine sanctuaries by far-ranging predators: commuting flights to the California Current System by breeding Hawaiian albatrosses. *Fisheries Oceanography*. 15:95-103. doi: 10.1111/j.1365-2419.2005.00350.x.

IPCC. 2007. Climate change 2007: the physical science basis. *In*: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M and Miller HL (eds), *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK. 996p.

IWC. 2010. Report of the workshop on cetaceans and climate change. *Journal of Cetacean Research and Management*. 11(SUPPL 2): 451-480.

Jay CV, Marcot BG, and Douglas DC. 2011. Projected status of the Pacific walrus (*Odobenus rosmarus divergens*) in the twenty-first century. *Polar Biology*. 34:1065-1084 doi:10.1007/s00300-011-0967-4.

Kaschner KR, Watson R, Trites AW and Pauly D. 2006. Mapping world-wide distributions of marine mammal species using a relative environmental suitability (RES) model. *Marine Ecology Progress Series*. 316:285-310. doi: 10.3354/meps316285.

Keller CA, Garrison L, Baumstark R, Ward-Geiger LI and Hines E. 2012. Application of a habitat model to define calving habitat of the North Atlantic right whale in the southeastern United States. *Endangered Species Research*. 18:73–87. doi: 10.3354/esr00413.

Knutti R and Sedláček J. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*. 3:369–373. doi:10.1038/nclimate1716.

Kovacs KM, Lydersen C, Overland JE and Moore SE. 2011. Impacts of changing sea-ice conditions on Arctic marine mammals. *Marine Biodiversity*. 41:1810194. doi: 10.1007/s12526-010-0061-0.

Laidre KL, Stirling I, Lowry LF, Wiig Ø, Heide-Jørgensen MP and Ferguson SH. 2008. Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecological Applications*. 18:S97-S125. doi: 10.1890/06-0546.1.

Link JS, Griffis R and Busch S (eds). 2015. NOAA Fisheries climate science strategy. US Department of Commerce, NOAA Technical Memorandum, NMFS-F/SPO-155. 70p.

Lewison R, Hobday AJ, Maxwell S, Hazen E, Hartog JR, Dunn DC, Briscoe D, Fossette S, O'Keefe CE, Barnes-Mauthe M, Abecassi M, Bograd S, Bethoney ND, Bailey H, Wiley D, Andrews S, Hazen L and Crowder LB. 2015. Dynamic Ocean Management: Identifying the critical ingredients of dynamic approaches to ocean resource management. *BioScience. 65:486-498.* doi: 10.1093/biosci/biv018.

Lynch PD, Nye JA, Hare JA, Stock CA, Alexander MA, Scott JD, Curti KL and Drew K. 2014. Projected ocean warming creates a conservation challenge for river herring populations. *ICES Journal of Marine Science*. doi: 10.1093/icesjms/fsu134.

Mannocci L, Catalogna M, Dorémus G, Laran S, Lehodey P, Massart W, Monestiez P, Van Canneyt O, Watremez P and Ridoux V. 2014. Predicting cetacean and seabird habitats across a productivity gradient in the South Pacific gyre. *Progress in Oceanography*. 120: 383–398. doi:10.1016/j.pocean.2013.11.005.

Maxwell SM, Hazen EL, Lewison RL, Dunn DC, Bailey H, Bograd SJ, Briscoe DK, Fossette S, Hobday AJ, Bennett M, Benson S, Caldwell MR, Costa DP, Dewar H, Eguchi T, Hazen L, Kohin S, Sippel T and Crowder LB. 2015. Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. *Marine Policy. 58:42-50.* doi:10.1016/j.marpol.2015.03.014.

McClure MM, Alexander M, Borggaard D, Boughton D, Crozier L, Griffis R, Jorgensen JC, Lindley ST, Nye J, Rowland MJ, Seney EE, Snover A, Toole C and Van Houtan K. 2013. Incorporating climate science in applications of the U.S. Endangered Species Act for aquatic species. *Conservation Biology*. 27:1222–1233. doi: 10.1111/cobi.12166.

Merow C, Smith M and Silander JA. 2013. A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter. *Ecography*. 36:1058–1069. doi: 10.1111/j.1600-0587.2013.07872.x

Moore, S, Watkins WA, Daher MA, Davies JR and Dahlheim, ME. 2002. Blue whale habitat associations in the northwest Pacific: analysis of remotely-sensed data using a Geographic Information System. *Oceanography*. 15:20-5.

Moore SE and Huntington HH. 2008. Arctic marine mammals and climate change: impacts and resilience. *Ecological Applications*. 18:S157-S165. doi: 10.1890/06-0571.1.

Morin X and Thuiller W. 2009. Comparing niche-and process-based models to reduce prediction uncertainty in species range shifts under climate change. *Ecology*. 90:1301–1313.

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ. 2010. The next generation of scenarios for climate change research and assessment. *Nature*. 463:747-756.

Myers RA. 1998. When do environment–recruitment correlations work? *Reviews in Fish Biology and Fisheries*. 8: 285-305. doi: 10.1023/A:1008828730759.

Nakicenovic N and Swart R (eds). 2000. *Intergovernmental panel on climate change special report on emissions scenarios: Summary for policy makers*. Cambridge University Press, Cambridge, UK.

NMFS. 2005. Recovery plan for the North Atlantic right whale. US Department of Commerce, National Marine Fisheries Service, Office of Protected Resources, Silver Spring, Maryland, USA.

NOAA. 2012. Final Rule: Endangered and Threatened Species; Threatened Status for the Arctic, Okhotsk, and Baltic Subspecies of the Ringed Seal and Endangered Status for the Ladoga Subspecies of the Ringed Seal. US Federal Register 77 FR 76706 https://alaskafisheries.noaa.gov/sites/default/files/finalrules/77fr76706.pdf.

NOAA. 2013. Final Rule: Removal of the sunset provision of the final rule implementing vessel speed restrictions to reduce the threat of ship collisions with North Atlantic right whales. US Federal Register 78 FR 73726. https://federalregister.gov/a/2013-29355.

NOAA. 2015. Final Rule: Takes of Marine Mammals Incidental to Specified Activities; U.S. Navy Training and Testing Activities in the Northwest Training and Testing Study Area. US Federal Register 80 FR 73555. https://federalregister.gov/a/2015-28894.

NOAA. *In draft*. Workshop Report: Protected Species Climate Vulnerability Assessment Methodology Development Expert Workshop. Silver Spring, MD. July 22 and 23, 2015. NOAA, NMFS, Office of Science and Technology. 40 p.

Nye JA, Link JS, Hare JA and Overholtz WJ. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Marine Ecology Progress Series*. 393:111-129. doi: 10.3354/meps08220.

Palacios DM, Baumgartner MF, Laidre KL, Gregr EJ. 2013. Beyond correlation: integrating environmentally and behaviourally mediated processes in models of marine mammal distributions. *Endangered Species Research*. 22:191-203.

Pinsky ML, Worm B, Fogarty MJ, Sarmiento JL and Levin SA. 2013. Marine taxa track local climate velocities. *Science*. 341:1239-1242. doi: 10.1126/science.1239352.

Plagányi ÉE. 2007. Models for an ecosystem approach to fisheries. FAO Fisheries Technical Paper. No 477. Rome, FAO. 108 p.

Poloczanska ES, Brown CJ, Sydeman WJ, Kiessling W, Schoeman DS, Moore PJ, Brander K, Bruno JF, Buckley LB, Burrows MT, Duarte CM, Halpern BJ, Holding J, Kappel CV, O'Connor MI, Pandolfi JM, Parmesan C, Schwing F, Thompson SA and Richardson AJ. 2013. Global imprint of climate change on marine life. *Nature Climate Change*. 3:919–925. doi:10.1038/nclimate1958.

Ragen TJ, Huntington HP and Hovelsrud GK. 2008. Conservation of Arctic marine mammals faced with climate change. *Ecological Applications*. 18:S166-S174. doi:10.1890/06-0734.1.

Randall DA, Wood RA, Bony S, Colman R, Fichefet T, Fyfe J, Kattsov V, Pitman A, Shukla J, Srinivasan J, Stouffer RJ, Sumi A and Taylor KE. 2007. Climate models and their evaluation. *In*: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge UK. 589–662p.

Redfern JV, Ferguson MC, Becker EA, Hyrenbach KD, Good C, Barlow J, Kaschner K, Baumgartner MF, Forney KA, Balance LT, Fauchald P, Halpin P, Hamazaki T, Pershing AJ, Qian SS, Read A, Reilly SB, Torres L and Werner F. 2006. Techniques for cetacean-habitat modeling: A review. *Marine Ecology Progress Series*. 310:271-295. doi: 10.3354/meps310271.

Redfern JV, Barlow J, Ballance LT, Gerrodette T, and Becker EA. 2008. Absence of scale dependence in dolphin-habitat models for the eastern tropical Pacific. *Marine Ecology Progress Series*. 363:1-14. doi:10.3354/meps07495.

Redfern JV, Mckenna MF, Moore TJ, Calambokidis J, Deangelis ML, Becker EA, Barlow J, Forney KA, Fiedler PC and Chivers SJ. 2013. Assessing the risk of ships striking large whales in marine spatial planning. *Conservation Biology*. 27:292–302. doi: 10.1111/cobi.12029.

Robinson LM, Elith J, Hobday AJ, Pearson RG, Kendall BE, Possingham HP and Richardson AJ. 2011. Pushing the limits in marine species distribution modeling: lessons from the land present challenges and opportunities. *Global Ecology and Biogeography*. 20:789-802. doi: 10.1111/j.1466-8238.2010.00636.x.

Saba VS, Griffies SM, Anderson WG, Winton M, Alexander MA, Delworth TL, Hare JA, Harrison MJ, Rosati A, Vecchi GA and Zhang R. 2016. Enhanced warming of the Northwest Atlantic Ocean under climate change. *Journal of Geophysical Research – Oceans*. 121:118–132. doi:10.1002/2015JC011346.

Shelden KEW, Sims CL, Vate Brattström L, Goetz KT and Hobbs RC. 2015. Aerial surveys of beluga whales (*Delphinapterus leucas*) in Cook Inlet, Alaska, June 2014. AFSC Processed Report 2015-03, 55 p. Alaska Fisheries Science Center, NOAA, NMFS. http://www.afsc.noaa.gov/Publications/ProcRpt/PR2015-03.pdf.

Silber GK, Vanderlaan ASM, Tejedor Arceredillo A, Johnson L, Taggart CT, Brown MW, Bettridge S and Sagarminaga R. 2012. Role of the International Maritime Organization in large whale vessel strike reduction: processes, measures and effectiveness. *Marine Policy*. 36:1221-1233. http://dx.doi.org/10.1016/j.marpol.2012.03.008.

Smith ADM, Sainsbury KJ and Stevens RA. 1999. Implementing effective fisheries-management systems – management strategy evaluation and the Australian partnership approach. *ICES Journal of Marine Science*. 56: 967–979.

Spencer PD, Holsman KK, Zador S, Bond NA, Mueter FJ, Hollowed AB and Ianelli JN. *In press*. Modeling spatially-dependent predation mortality of eastern Bering Sea walleye pollock and its implications for stock dynamics under future climate scenarios. *ICES Journal of Marine Science*.

Spillman CM, Alves O and Hudson DA. 2013. Predicting thermal stress for coral bleaching in the Great Barrier Reef using a coupled ocean-atmosphere seasonal forecast model. *International Journal of Climatology*. 33:1001–1014. doi: 10.1002/joc.3486.

Stock CA, Alexander MA, Bond NA, Brander K, Cheung WWL, Curchitser EN, Delworth TL, Dunne JP, Griffies SM, Haltuch MA, Hare JA, Hollowed AB, Lehodey P, Levin SA, Link JA, Rose KA, Rykaczewski RR, Sarmiento JL, Stouffer RJ, Schwing FB, Vecchi GA and Werner FE. 2011. On the use of IPCC-class models to assess the impact of climate on living marine resources. *Progress in Oceanography*. 88:1–27. doi:10.1016/j.pocean.2010.09.001.

Stock CA, Pegion K, Vecchi GA, Alexander MA, Tommasi D, Bond NA, Fratantoni PS, Gudgel RG, Kristiansen T, O'Brien TD, Xue Y and Yang X. 2015. Seasonal sea surface temperature anomaly prediction for coastal ecosystems. *Progress in Oceanography*. 137A:219-236. doi:10.1016/j.pocean.2015.06.007.

Sydeman WJ, Thompson SA, Santora JA, Koslow JA, Goericke R and Ohman MD. 2015. Climate-ecosystem change off southern California: Time-dependent seabird predator-prey numerical responses. *Deep-Sea Research II*. 112:158-170. doi:10.1016/j.dsr2.2014.03.008

Taylor B, Wade PR, DeMaster DP and Barlow J. 2000. Incorporating uncertainty into management models for marine mammals. *Conservation Biology*. 14:1243–1252.

Thomas PO, Reeves RR and Brownell Jr RL. 2015. Status of the world's baleen whales. *Marine Mammal Science*. Article first published online: 53p. doi: 10.1111/mms.12281.

Trathan PN, Forcada J, Murphy EJ. 2007. Environmental forcing and Southern Ocean marine predator populations: effects of climate change and variability. *Philosophical Transactions of the Royal Society*. 362: 2351-2365.

Wade PR. 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science*. 14:1-37. doi: 10.1111/j.1748-7692.1998.tb00688.x.

Winn HE, Price CA, and Sorensen PW. 1986. The distributional biology of the right whale (*Eubalaena glacialis*) in the western North Atlantic. *Report of the International Whaling Commission (special issue).* 10:129–138.

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Agenda

Workshop on

Best Approaches and Needs for Projecting Marine Mammal Distributions in a Changing Climate

12-14 January 2016

Santa Cruz, California

Workshop Objectives:

- Explore modeling or other means to assess future changes in distribution and abundance of marine mammal species;
- Identify metrics relevant to assessing physical changes and biological responses of marine mammals;
- Identify one or more exemplar species/population(s) for assessing methodologies or metrics (depending on the timing, exemplar species might include those considered most vulnerable in the climate change vulnerability assessments);
- Identify next steps for performing these studies;
- Produce draft and final reports of the findings.

<u>Day 1</u>

8:30-9:00

Opening, introductions, charge to the workshop, housekeeping

9:00-10:30

Assessing the effects of climate change on marine ecosystems (*15 minute presentations*)

> *"Approaches/models used to characterize, and to forecast, physical and biological shifts in marine ecosystems in a changing climate"* (Alistair Hobday, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, Australia)
>
> "*Advances in seasonal to century-scale global climate and earth system predictions for marine resource applications*" (Charles Stock, NOAA's Geophysical Fluid Dynamics Laboratory, Princeton University)

Assessing the effects of climate change on marine vertebrate occurrence and distribution

> "*Climate change and marine vertebrates*" (William Sydeman, Farallon Institute for Advanced Ecosystem Research, Petaluma, CA)
>
> "*Brief overview of literature related to approaches used to predict marine mammal distribution; and conclusions of the July 2015 'Protected Species Climate Vulnerability Assessment' Workshop*" (Matt Lettrich, NMFS Office of Science and Technology)
>
> "*Using environmental correlates to forecast marine mammal distributions*" (Karin Forney and Elizabeth Becker, NMFS/SWFSC)

10:30-10:45 Coffee Break

10:45-12:00

"*Understanding climate responses from genes to predator communities in the Southern Ocean*" (Jaume Forcada, British Antarctic Survey)

"*Using global climate models to project bearded and ringed seal distribution through the 21st century*" (Peter Boveng, NMFS National Marine Mammal Laboratory)

"*Drivers that influence phenological changes in marine mammals, particularly in the Arctic and sub-Arctic Pacific*" (Kate Stafford, University of Washington)

"*Barents Sea marine mammals: understanding and modeling ecosystem interactions*" (Daniel Howell, Norway Institute of Marine Research)

Discussion:

Begin synthesizing list of models/approaches that might be useful in predicting

marine mammal distribution based on the morning's presentations

12:00-1:00 Lunch

1:00-2:30

Additional presentations (if needed)

Discussion:

Identify any additional models/approaches not discussed thus far in the workshop that might be useful in predicting marine mammal distribution.

Begin developing a list of the *features* of the various models that might be useful in predicting marine mammal distribution. Which features *would not* apply? Are there other useful features not discussed thus far?

2:30-2:45 Coffee Break

2:45-4:30

Discussion:

Continue discussing features of various models most salient to forecasting marine mammal distribution.

Assess strengths/weaknesses of the various models/approaches identified thus far.

Begin discussion of constructing a matrix that summarizes features of various models and helps describe advantages/disadvantages of each.

Day 2

9:00- 10:30

Review of Day 1. Complete anything not addressed in Day 1.

"*A new perspective on the foraging ecology of apex predators in the California Current: results from a fully coupled ecosystem model*" (Jerome Fiechter, UC, Santa Cruz)

Additional presentations, if needed, on approaches/models used to characterize marine vertebrate distribution. Complete list of approaches/models that might be used in predicting marine mammal distribution.

Continue identifying/assessing, and complete a list of desirable attributes of models useful in characterizing marine mammal distribution.

Construct matrix of approaches/models and strengths/weaknesses of each.

10:30-10:45 Coffee Break

10:45-12:00

Discuss/decide whether the next few items should be addressed in break-out groups, as a workshop as a whole, or in combination of both

Discussion of species/populations that might be used in assessing or illustrating use of approaches for predicting distribution (*i.e.*, which marine mammal populations would be suitable for future modeling case studies and analytical exercises? Which populations most vulnerable? Which are data-rich, which are data-poor?)

Pinniped vs. cetacean break-out groups (??) Which models would lend themselves to predicting pinniped vs. cetacean distributions? Which populations are good candidates for future modeling case studies?

Continue constructing a matrix of strengths/weaknesses of various approaches/models.

12:00-1:00 Lunch

1:00-2:30

In break-out groups or as a workshop as a whole.

Work to complete strengths/weaknesses matrix. Prioritize/rank the various models; rank model attributes.

Develop list of illustrative species that might reasonably be used in modeling exercises.

Develop framework and main components of a final report; begin developing suggested guidance for post-workshop action/analyses.

Determine initial report drafting assignments; if time allows, begin initial drafting.

Day 3

9:00-10:30

Continue developing, fine-tuning matrix.

Concluding discussion regarding work to date; work to finalize strengths/weaknesses matrix, prioritized list of approaches/models (and attributes), and list of species/populations for future analysis.

10:30-10:45 Coffee Break

10:45-12:00

Finalize ranked model/attribute matrix, and list of species/populations for future analysis.

Next steps, plans for workshop report preparation, drafting assignments, timelines, etc.

Misc.

12:00 **Adjourn**