2. EXPLAINING EXTREME OCEAN CONDITIONS IMPACTING LIVING MARINE RESOURCES

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The Food and Agriculture Organization of the United Nations (FAO) (2016) estimates for 2014 that the global trade in fish and fishery products was near $148 billion (U.S. dollars) and employed close to 38 million people. Healthy ecosystems are also important for sustaining coastal marine tourism activities estimated globally to be over $160 billion (U.S. dollars) per year (FAO 2016). Additionally, estimates from the World Bank (2017) indicate that additional benefits could be gained (e.g., $83 billion dollars in 2012) with higher sustainable harvest attainable due to larger fish biomass; lower fishing costs due to lower fishing effort; and higher unit prices of landings due to improved species composition of the global stock. Given the important socioeconomic value of coastal and marine resources [Fisheries Economics of the United States (NMFS 2015)], when confronted with fluctuations in fisheries or significant changes in marine ecosystems, stakeholders (e.g., the public, commercial and sport fishing industries, fishery managers, scientists, coastal community conservationists, environmental groups, and the media) are increasingly asking the scientific research community if the observed, and perceived to be unprecedented, extremes and trends in ocean conditions that impact living marine resources are due to natural variability (i.e., potential recurrences of past events) or a manifestation of long-term changes in climate (i.e., "new normals" or "regime shifts" not experienced before; King et al. 2005).

A clear understanding of the background conditions and underlying processes resulting in extremes and trends in ocean conditions impacting living marine resources are of value to guide decision making. Without this knowledge, policy, planning, and decision makers face greater uncertainties in making informed decisions to minimize disruptive impacts, to guide management choices to better prepare for future changes, and to inform sustainability strategies to ensure the continued benefits of healthy and productive marine ecosystems. Regional Fisheries Management Councils in the United States, and similar regulatory bodies in other parts of the world, allow participatory governance by knowledgeable people with a stake in their individual regions to develop marine fisheries management plans (such as fishing seasons, quotas, and closed areas) based on sound scientific advice. When confronted with extreme ocean conditions impacting marine ecosystems and fisheries, in order to make informed decisions on how to best manage the impacted living marine resources, fisheries management organizations can use answers to four fundamental questions: *What happened? Why did it happen? Is it predictable? and What is the likelihood of it happening again?* To answer these questions, the *BAMS* 2016 report "Explaining Extreme Events from a Climate Perspective" includes three studies that strive to connect attribution of an extreme ocean condition with the socioeconomic impacts on living marine resources: "A multifactor analysis of the record 2016 Great Barrier Reef bleaching" (Lewis and Mallela 2018); "Ecological impacts of the 2015/16 El Niño in the central equatorial Pacific" (Brainard et al. 2018); and "Multiyear extreme ocean temperatures with impacts on living marine resources off the U.S. West Coast during 2016" (Jacox et al. 2018).

These and previous studies (see Table 2.1 for selected examples) describe physical and biogeochemical characteristics impacting living marine resources, and strive to identify climate mechanisms and forcings that led to their occurrence. Large-scale patterns of coupled ocean–atmospheric circulation are assessed in terms of their influence on the statistics of extreme events regionally. The goal of these studies is to explain the effects of individual extreme ocean condition events (e.g., marine heat waves, Hobday et al. 2016; Ummenhofer and Meehl 2017), or cumulative effects of trends and trajectories in ocean conditions that can result in abrupt shifts, and potentially to tipping points, in marine ecosystems that can last for prolonged periods (e.g., deYoung et al. 2008; Möllmann et al. 2015), and ultimately provide process-understanding of the resulting impacts (e.g., Rocha et al. 2015). Such effects include the physical or biogeochemical characteristics of the environment (temperature, salinity, nutrient levels), ecosystem

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Table 2.1. Examples of climate attribution studies of an extreme ocean conditions impacting on living marine resources (also see Brainard et al. 2018, Jacox et al. 2018, and Lewis and Mallela 2018, chapters 5, 6, and 28, in this report).

Title	Author	Geographic Location	Timing of Event
What caused the Sacramento River fall Chinook stock collapse?	Lindley et al. 2009	U.S West Coast/ California Current	2008
Climate change impact on the northeast Atlantic cusk	Hare et al. 2012	Gulf of Maine, Georges Bank, and the Scotian Shelf	mid-1990s
West Coast Dungeness crab fishery	Marshall et al. 2017	U.S. West Coast	2016
New England Cod Collapse	Meng et al. 2016	Gulf of Maine	2014
Beluga whale migration altered by delayed sea ice formation	Hauser et al. 2016	Eastern Chukchi Sea and Eastern Beaufort Sea	2004–2012
California Current large marine ecosystem	Cavole et al. 2016	Northeast Pacific	2014–2016

structure (changes in community make-up, shifts between benthic and pelagic production), fisheries (shifts in distribution and/or abundance of important commercial and recreational species), and the socioeconomic impacts on the human communities that depend on them.

For example, consider recent extreme regional ocean conditions events resulting in changes in ecosystems and regional fishery stocks (e.g., Cavole et al. 2016) following a previous and perceived to be unprecedented collapse in some of the same fishery stocks ten years earlier (e.g., Lindley et al. 2009). Critical risk management questions are whether there has been a shift in the probability of ocean conditions leading to such an extreme impact, and whether living marine resource managers can, or should, adapt to an apparent increased risk[1]. Assessments of how natural and human causes influence the probability of extremes and trends in ocean conditions impacting living marine resources can be used to assess vulnerabilities and to guide adaptation and mitigation decision making by fisheries management councils to improved resilience in a varying and changing climate (e.g., Hare et al. 2016).

Management decisions on how to respond to extreme environmental conditions will clearly benefit from a mechanistic understanding. Such understanding can provide quantitative estimates of the relative contributions of natural variability, anthropogenic climate change, and other factors through fraction of attributable risk (FAR; Stott et al. 2004) and other statistical analyses. The added insights will assist fisheries management bodies in considering strategies to deal with extreme events, anticipate the risks (and their confidence intervals) to human and natural systems, and thereby support management and protection of marine resources at national regional, state, and local levels.

In the short term, these studies provide resource managers with better understanding of the current and future risk of extreme ocean conditions impacting living marine resources that enable better-informed policies, planning, and decisions made based upon the best available scientific understanding. In the longer term, the rigorous understanding of the predictability and future risk of extreme ocean conditions can advance both the science and decision criteria needed to improve the certainty of threat assessments for ocean conditions impacting commercial and recreational fisheries and other marine resources. While the impacts on, and responses by, living marine resources are typically the result of the cumulative effect of multiple stressors, risk-based analyses of extreme ocean conditions are of value to inform integrated ecosystem-based fisher-

[1] www.st.nmfs.noaa.gov/ecosystems/climate/activities/assessing-vulnerability-of-fish-stocks and www.st.nmfs.noaa.gov/ecosystems/climate/national-climate-strategy

ies management decisions (e.g., Fulton et al. 2013; NOAA's 2016 Ecosystem Based Fisheries Management Roadmap, www.st.nmfs.noaa.gov/Assets/ecosystems/ebfm/EBFM_Road_Map_final.pdf) to maximize the global, national, regional, and local socioeconomic value of living marine resources.

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