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North America's Iconic Marine Species at Risk Due To Unprecedented Ocean Warming

By Charles H. Greene

Global mean temperatures during 2016 are on pace to break the historical records set sequentially during 2014 and 2015. Coincident with this record-setting atmospheric warming, sea surface temperatures (SSTs) along both coasts of North America have been rising more rapidly than in most other coastal waters of the world (Figure 1). In the Gulf of Maine, SSTs have increased more rapidly during recent years than in 99.9% of the global ocean (Mills et al., 2013; Pershing et al., 2015). A multiyear heat wave along the west coast, from Mexico to Alaska, has led to SSTs exceeding historical highs by as much as 3°C during the past three years (Bond et al., 2015; Hartmann, 2015; Cavole et al., 2016). As coastal ocean heat waves become more frequent and persistent (Scannell et al., 2016), ecosystem regimes are shifting and species ranges are both contracting and expanding. In the ensuing shuffle, many of North America's most iconic marine species are in decline and in some cases are facing the threat of local extinction.

The Gulf of Maine's rapid warming poses a threat to three of New England's most well-known species, the Atlantic cod, the northern right whale, and the American lobster (Figure 2). Fisheries based on cod and lobster support maritime traditions as old as New England itself, while whale watching currently attracts over a million visitors annually to the region. Among these three species,

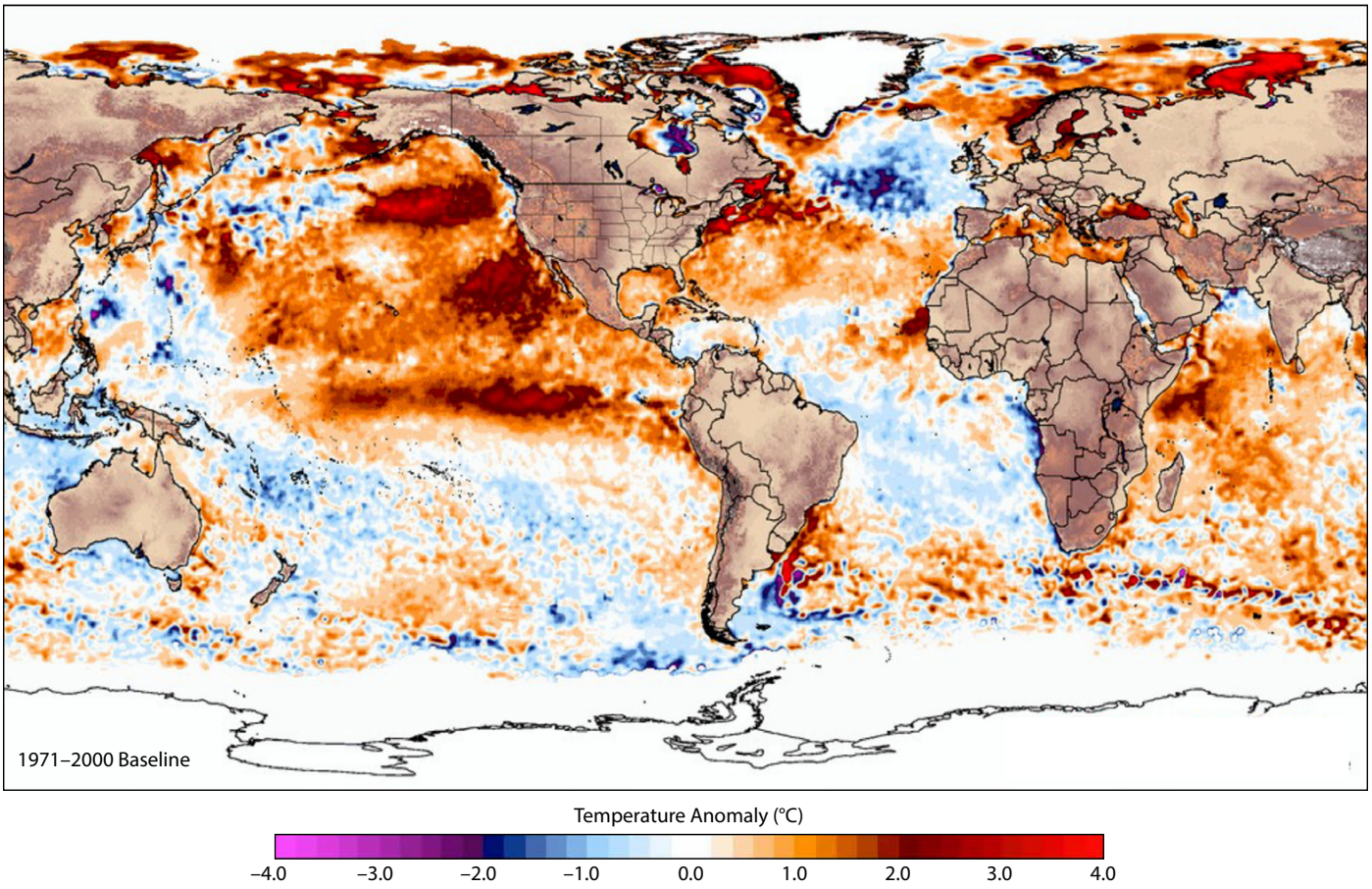

FIGURE 1. Sea surface temperature (SST) anomalies for August 2015. Note the unusually high SST anomalies along both coasts of North America. *Image from Climate Reanalyzer, Climate Change Institute, University of Maine*

cod is the one currently being impacted negatively by warmer temperatures in the Gulf of Maine, while the other two face imminent threats from continued warming as mediated by their interactions with other species.

Throughout the North Atlantic, cod recruitment and growth responses vary by region, with southern (northern) stocks responding more favorably to cooling (warming) temperatures (Greene et al., 2013). Cod stocks near the species' southern limit, like those in the Gulf of Maine, fare poorly under warming conditions, exhibiting lower recruitment, slower growth, and greater susceptibility to overfishing (Pershing et al., 2015). Direct physiological responses as well as changing prey conditions appear to be responsible. As warming continues, southern cod stocks will be increasingly stressed, and the Gulf of Maine will likely be unable to support this productive fishery in future decades.

In addition to threats posed by ship strikes and entanglement in fishing gear, the endangered northern right whale is also at risk from warming ocean temperatures. The recovery of the right whale population has exhibited a 10-year cycle during the past three decades, alternating from rapid population growth during the 1980s, to slower growth during the 1990s, and then back to rapid growth during the 2000s (Meyer-Gutbrod and Greene, 2014). This decadal cycle has been linked to the effects of climate-induced changes in prey availability on female calving rates (Meyer-Gutbrod et al., 2015). The copepod species *Calanus finmarchicus* is the right whale's primary source of nutrition, and its abundance in the Gulf of Maine has been correlated with basin-scale changes in the North Atlantic and Arctic climate systems (Greene et al., 2013). If the Gulf's rapid warming continues, then optimal *C. finmarchicus* habitat is predicted to shift northward, reducing its population in the Gulf (Reygondeau and Beaugrand, 2011). This change in prey availability will likely have a strong impact on the right whale population, eventually forcing it to shift its foraging grounds or significantly alter its diet.

The Gulf of Maine lobster population has been thriving with the recent warming trend; however, this situation is unlikely to continue. Bacterial epizootic shell disease (ESD; Figure 3), which devastated the Long Island lobster fishery during the 1990s and has severely impacted the lobster fisheries of Rhode Island and Massachusetts more recently, will soon begin to take its toll in the Gulf (Maynard et al., 2016). ESD's range has been shifting northward with warming ocean temperatures, and its infection rate has started to increase among lobsters caught off southern Maine. Fishermen and managers alike

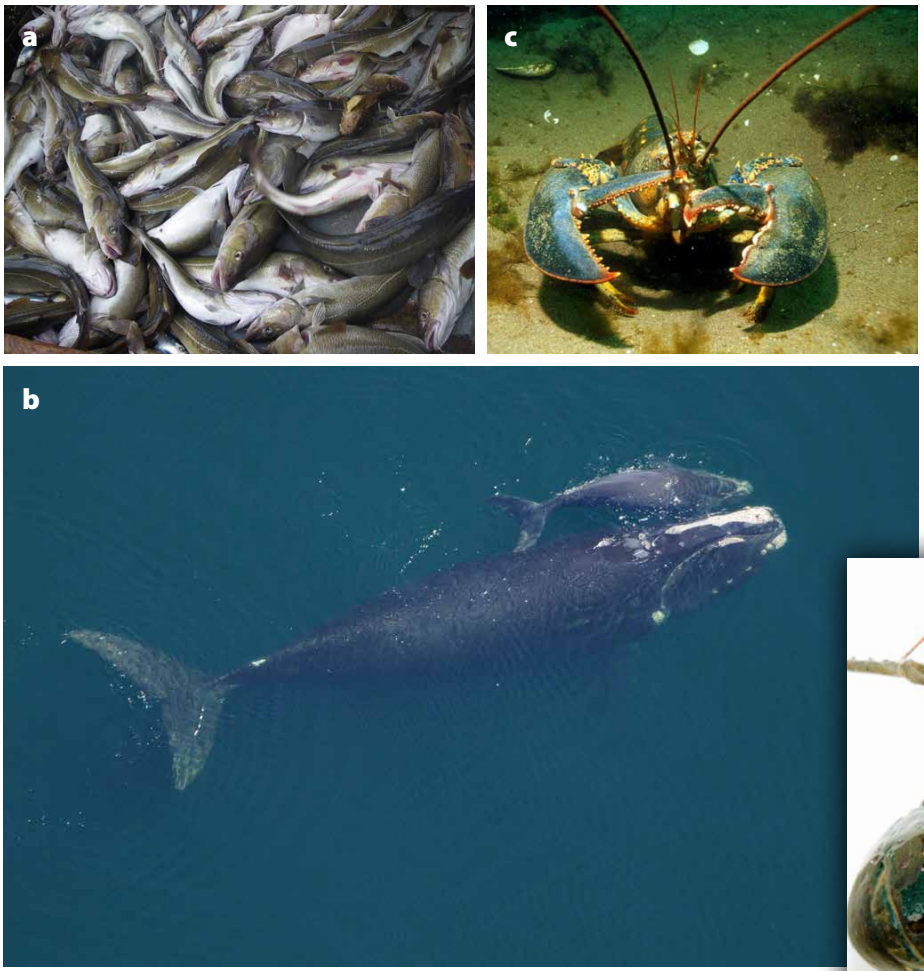

FIGURE 2. (a) Atlantic cod caught in the Gulf of Maine. *Image provided by Andrew Pershing, Gulf of Maine Research Institute* (b) Northern right whale mother and calf swimming near the surface. *Photo credit: Kevin Robinson, Cetacean Research and Rescue Unit* (c) American lobster scavenging along the seafloor in Canada's Bay of Fundy. *Image from the collection of the late Peter Scoones*

FIGURE 3. Epizootic shell disease (ESD) developing along the dorsal surface of an American lobster's carapace. *Image provided by Charlotte Eve Davies, Institute of Ocean Sciences and Limnology, Universidad Nacional Autonoma de Mexico*

must begin to prepare now for the ESD outbreak that is almost certain to come.

The extensive ocean warming along the west coast poses similar threats to several iconic species of salmon, marine mammals, and starfish. In California, Chinook salmon stocks are suffering from nutritional stresses associated with warmer, less productive coastal conditions (Figure 4; Kilduff et al., 2015). In addition, because this species is anadromous, it is also suffering from the environmental stresses brought about by California's drought. This combination of stresses, both linked to warming SSTs, has already resulted in mass mortalities and year-class recruitment failures. As with cod, the southern stocks of Chinook salmon will be increasingly stressed with continued warming, eventually threatening many California stocks with local extinction.

Among the many species of marine mammals and seabirds being impacted by warming coastal waters, California's sea lion population is being hit especially hard (Figure 5; http://www.nmfs.noaa.gov/pr/health/mmume/californiasealions2013.htm; Leising et al., 2015; McClatchie et al., 2016). With a warming-induced decline of forage-fish populations, sea lion females are traveling greater distances and spending more time away from rookeries to forage for prey. This has resulted in pups weaning prematurely, with record numbers of them found stranded and starving on beaches, especially in southern California and the Channel Islands. The California sea lion population has repeatedly recovered from short-term population crashes associated with El Niño events in the past (Melin et al., 2010); however, continued ocean warming may jeopardize the long-term viability of this species' southern rookeries, where greater than 90% of the population breeds.

From a biodiversity perspective, perhaps the most alarming event during the recent warming has been the collapse of nearly every sea star species below and between Pacific tides from California to Alaska. Having caught the scientific community by surprise, the epidemiology of this multispecies sea star wasting disease is still poorly understood (C.D. Harvell, Cornell University, *pers. comm.*, June 2016). A single viral pathogen is thought to be behind this temperature-mediated epizootic of unprecedented geographic extent (Hewson et al., 2014; Eisenlord et al., 2016). Laying waste to such keystone predators as the ochre star (*Pisaster ochraceous*) in the intertidal (Figure 6) and the sunflower star (*Pycnopodia helianthoides*) in the subtidal (Figure 7), sea star wasting disease is perturbing the West Coast's rocky seashore communities on a scale previously unimaginable (Pfister et al., 2016; Greene, 2016) and with no end predicted into the foreseeable future.

The ecological tragedies playing out on both coasts of North America result from the interaction between natural climate processes and the relentless rise in anthropogenic climate forcing. Over short but societally relevant time scales, it is difficult to tease apart the greenhouse warming signal from the natural modes

FIGURE 4. Returning Central Valley Chinook salmon in the Yuba River, California. *Image from Jacob Katz, California Trout Inc.*

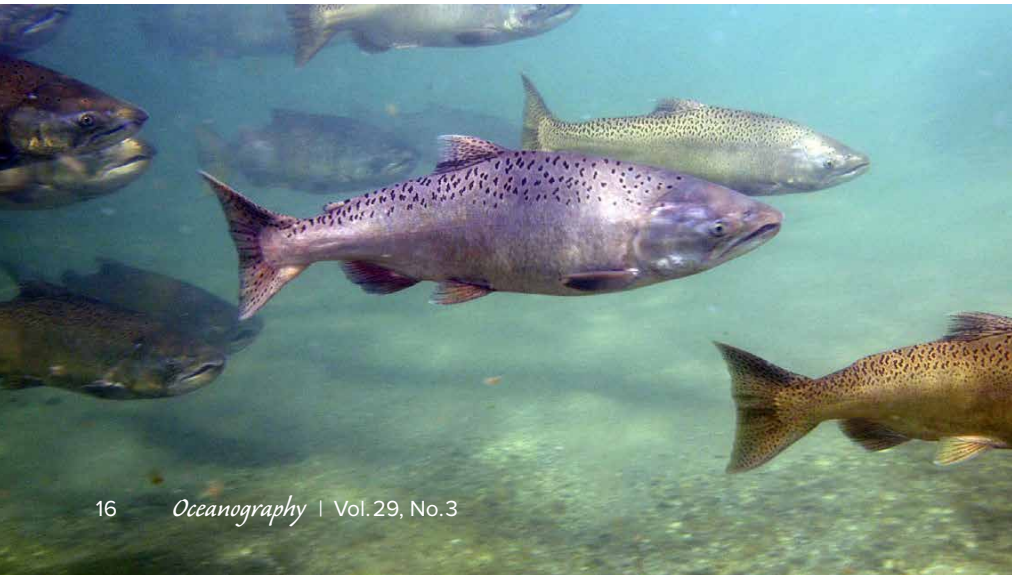

FIGURE 5. Nutritionally stressed California sea lion pups observed in the Channel Islands during September 2015. *Image provided by Katherine Prager, University of California Los Angeles; researchers had approval to approach sea lions under NMFS permit 16087-02 issued to the National Marine Mammal Laboratory*

FIGURE 6. The ochre star, *Pisaster ochraceous,* showing symptoms of wasting disease in intertidal waters of British Columbia, Canada, during July 2014. The image captures the early signs of lesions, loss of turgor, and arm-twisting at the top, and dead and decomposing stars in the foreground. *Image provided by Drew Harvell, Cornell University*

of climate variability, ranging from the relatively brief but powerful El Niño-Southern Oscillation cycles to the decadal-scale cadences of the Arctic Oscillation, the Pacific Decadal Oscillation, the North Pacific Gyre Oscillation, and the Atlantic Multidecadal Oscillation (Chavez et al., 2011; Greene et al., 2013; Bond et al., 2015; Hartmann, 2015; Kilduff et al., 2015; Pershing et al., 2015). Each of these climate modes waxes and wanes to its own rhythm; however, recently, shifts to the warm phases of several of them appear to have coincided with a resumption of rapid climate warming. This coincidence of natural and anthropogenic warming has been wreaking havoc with North America's marine ecosystems. The resulting demise of many of North America's most iconic marine species provides yet another warning to society that a changing climate will leave future generations with an ocean much different than the one we grew up with.

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FIGURE 7. (a) Sunflower stars, *Pycnopodia helianthoides*, cover a rock outcropping in the subtidal waters of British Columbia, Canada, on October 9, 2013. (b) After wasting disease has ravaged the population, the same rock outcropping on October 29, 2013, has been denuded of seastars. *Images provided by videographer Neil McDaniel*