ICES CM 2013/B:79

Supporting fisheries management under climate change: lessons from the 2012 ocean heat wave

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Summary
Unprecedented warm temperatures across much of the Northwest Atlantic in 2012 triggered rapid ecological responses in many species and revealed weaknesses in both fisheries economic and management systems. In the Gulf of Maine, warmer water temperatures led to earlier inshore migration and faster molting rates of American lobster, which supported record landings but also contributed to a price collapse that threatened the economic viability of the fishery (Mills et al., 2013). This experience highlights limitations of current scientific and management approaches as well as advances that may be necessary to sustain fisheries and fishing communities in a variable and warming climate. Improved capacities to detect and predict ecosystem impacts of climate change and fishery management systems that can adapt to ecosystem changes and respond to variability will be critical for achieving these outcomes. These advances will be dependent on the (1) maintenance and expansion of observing systems to provide data that support predictive modeling efforts; (2) development of models of climate change impacts on marine ecosystems, resources, and fishing communities; and (3) adaptation of management tools so that they do not rely on stationarity in ecosystem and population dynamics (Mills et al., 2013).

Introduction
Extreme events are expected to become more common as climate change progresses (Tebaldi et al., 2006; Hansen et al., 2012). During 2012, a record heat wave affected a large portion of the northwest Atlantic Ocean (see Pershing et al., ICES CM 2013/B:35). Marine species responded by shifting their geographic distribution and seasonal cycles, both of which affected fisheries targeting those species. The 2012 northwest Atlantic heat wave provides an opportunity to better understand how ecosystems respond to extreme warm events and how fishery management approaches may need to adapt to be effective under warming and increasingly variable climate conditions (Mills et al., 2013).

Materials and Methods
NOAA's optimally-interpolated sea surface temperature (SST) data set (Reynolds et al. 2007) was used to characterize the 2012 ocean heat wave. We created a climatological temperature map for each day by averaging the values in each 0.25° spatial grid cell for that day over the period 1982-2011. We then determined SST anomalies for each day by subtracting the corresponding daily climatology (see Pershing et al., ICES CM 2013/B:35). Monthly landings data were used to document changes in the American lobster fishery. Data from 1990-2011 were obtained from NOAA's Commercial Fisheries Statistics (NOAA Office of Science and Technology 2013), and data for 2012 were obtained from Maine's Department of Marine Resources. Our preliminary characterization of changes in the Gulf of Maine ecosystem during 2012 was based on reports of unusual species by fishermen and scientists.

Results
The 2012 ocean heat wave was the largest and most intense warm period documented in existing SST records (see Pershing et al., ICES CM 2013/B:35). From Cape Hatteras to Iceland and northward into the Labrador Sea, SST was 1-3 °C warmer than the 1982-2011 climatology, a level of warming that is on par with the mean SST projected for the end of the century (Meehl et al., 2007). The very warm temperatures bought some species normally found in the mid-Atlantic into the Gulf of Maine, and

fisheries responded rapidly. For example, longfin squid (*Doryteuthis pealeii*) were present in Maine inshore waters, and local fisheries and markets developed within the season (Frederick 2012).

Important existing fisheries were also impacted. The inshore migration of and fishery for American lobsters (*Homarus americanus*) is closely tied to temperature. In the spring of 2012, temperatures were similar to those normally experienced three weeks later in the season. Lobsters moved inshore earlier, and the fishery began in earnest. Landings rose sharply three weeks ahead of the typical fishing season, and high landings extended three weeks later at the end of the season. However, the record landings led to an economic crisis, as they outstripped the processing capacity and market demand for the product. Ex-vessel prices dropped as low as $1.25 per pound (Dicolo and Friedman 2012), which threatened the economic viability of both U.S. and Canadian lobstermen.

Discussion

Experiences in the Gulf of Maine during 2012 demonstrated how complex relationships between physical, biological, and economic systems can rapidly affect fisheries, highlighting the need for climate change adaptation planning within fisheries management. Improved capacities to detect and predict ecosystem impacts of climate change and fishery management systems that accommodate ecosystem changes will be critical. Recommendations include:

- ***Develop climate-ecosystem models.*** Much international progress has been made in refining models of the climate system. Extending these models to link warming trends and extreme events associated with climate change to marine ecosystem and fishery impacts would help fishery managers identify and evaluate climate adaptation strategies.
- ***Enhance management-relevant predictive capacities***. Many of the biological responses to the 2012 conditions could have been predicted using data that are collected by ocean observing systems. However, to guide resource management, these data must be integrated into models of biological and fishery responses to physical changes at time scales relevant to management decisions.
- ***Identify adaptation needs within fisheries management.*** Fishery management structures and processes will need to adapt to future climate conditions. Three adaptation needs became apparent during 2012: (1) consider how permitting processes affect access to target species that move into new areas, (2) plan for shifting management boundaries as species distributions shift, and (3) decrease reliance on stationary baselines in management tools and reference points.

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