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Long Time Series in US Fisheries Oceanography

By Sam McClatchie, Janet Duffy-Anderson, John C. Field, Ralf Goericke, Dave Griffith, David S. Hanisko, Jonathan A. Hare, Joanne Lyczkowski-Shultz, William T. Peterson, William Watson, Edward D. Weber, and Glenn Zapfe

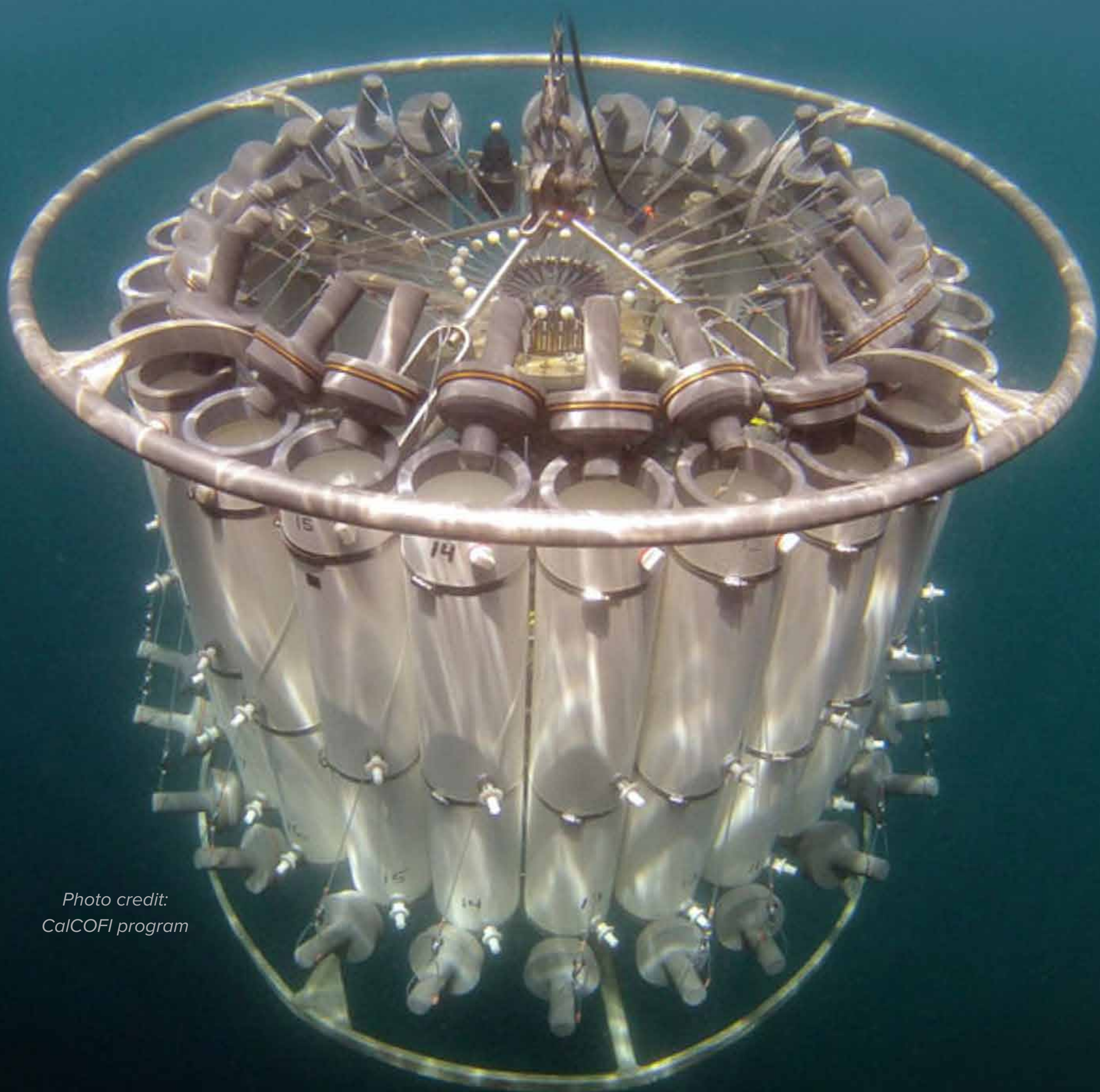

Photo credit: CalCOFI program

ABSTRACT. Few fisheries oceanography surveys in the United States have sampled hydrography and ichthyoplankton or juvenile fishes for 15 years or more. We describe six long time series surveys, including three from the California Current System, and one each from Alaska (Gulf of Alaska, Bering Sea, and the Arctic), the Northeast US Shelf, and the Gulf of Mexico. We examine the applications of long time series data as well as the output of published analyses, Web-based graphical summaries, and quality controlled data to the broader scientific community (including resource managers and stakeholders). Potential improvements to the surveys using new technologies are evaluated, and possible changes in survey design are discussed. We conclude with a summary of the benefits derived from these long time series fisheries oceanography surveys and make the case for their continuation.

INTRODUCTION

Long time series are critical to fisheries oceanography in order to evaluate the effects of climate variability and change on fishery populations and to provide observations on population abundance, distribution, and habitat use. Numerous reviews have been published, including Karl et al. (2001), Ohman and Venrick (2003), Karl (2010), Edwards et al. (2010), Koslow and Couture (2013), McClatchie (2014), and Koslow and Couture (2015), but none that we are aware of have compared long time series fisheries oceanography programs currently operating in the United States. Here, we define long time series in fisheries oceanography as surveys longer than 15 years that sample either juvenile fish or ichthyoplankton (fish eggs and larvae) combined with fields of oceanographic properties.

In this review, we consider California Cooperative Oceanic Fisheries Investigations (CalCOFI) and Rockfish Recruitment and Ecosystem Assessment Survey (RREAS) results, both conducted off central and southern California; the Newport Hydrographic Line off Oregon; Ecosystems & Fisheries-Oceanography Coordinated Investigations (EcoFOCI) in the Gulf of Alaska and the Bering, Beaufort, and Chukchi Seas; the Ecosystem Monitoring Program (EcoMon) on the Northeast US Shelf; and the Southeast Area Monitoring and Assessment Program (SEAMAP) in the Gulf of Mexico. We very briefly describe each survey, summarize applications of the data, and describe how the data may be obtained. We conclude by discussing how the surveys might be optimized using new technologies and modified survey designs, examining the problems as well as the advantages of change.

SUMMARY OF SURVEYS AND APPLICATIONS

California Cooperative Oceanic Fisheries Investigations (CalCOFI)

CalCOFI was originally established to determine the cause of the collapse of the Pacific sardine fishery by measuring as broad a suite of environmental variables as possible. The CalCOFI program may well be unique among fisheries oceanography programs because from its inception, its aim was to understand the ecology of fishes, specifically Pacific sardine, in its oceanographic context (Clark and Marr, 1955; McClatchie, 2014). The collection of oceanographic data has broadened over the years from basic hydrographic parameters to a fairly exhaustive characterization of an ecosystem and its physical environment. The breadth of the survey permitted the focus to expand well beyond sardine, such that CalCOFI and the associated National Science Foundation (NSF) California Current Long Term Ecological Research (CC-LTER) program are now used to assess the state of the California Current System (CCS) by characterizing the hydrographic, biogeochemical, and trophic state of the CCS in detail. Today, CalCOFI surveys (Figure 1) are made quarterly, although they were more frequent in the 1950s (McClatchie, 2014). The classic focus is on ichthyoplankton, zooplankton, and hydrography rather than on adult fish or juveniles. Supplementary sampling focused on fish and has largely been restricted to associated fisheries surveys that run back-to-back with CalCOFI surveys in spring and summer. CalCOFI measurements are known for the attention given to calibration of biological, physical, and chemical methods, and the rigor with which different methodologies are compared (Ohman and Smith, 1995). Nevertheless, CalCOFI sampling differs not only in terms of temporal and spatial frequency (Figure 1B) but also in terms of the properties sampled. Taxonomic resolution has been increased over time and is now consistent back to 1966. McClatchie (2014) provides a comprehensive review of the fisheries oceanography aspects of CalCOFI.

CalCOFI data are used both in support of stock assessments and for ecosystem and climate research (McClatchie, 2014). The best-known application of CalCOFI ichthyoplankton data to stock assessment is the Daily Egg Production Method (DEPM) used to estimate the spawning stock biomass of Pacific sardine (*Sardinops sagax*). DEPM was originally developed to assess northern anchovy (*Engraulis mordax*) spawning stock biomass (Lasker, 1985), but a daily larval production method was also shown to have potential use in the assessment of Pacific hake (*Merluccius productus*) (Lo, 2007), rockfishes (Ralston et al., 2003; Ralston and McFarlane, 2010), and Pacific mackerel (*Scomber japonicus*) (Lo et al., 2010). The method was successful for two rockfish species, but had limited utility for the more widely distributed Pacific mackerel. There are five cases (sardine, bocaccio [*Sebastes paucispinis*], cowcod [*S. levis*], shortbelly rockfish [*S. jordani*], and California sheephead [*Semicossyphus pulcher*]) where CalCOFI surveys provide fishery-independent data used in current stock assessments, one case (Pacific mackerel) where the data have been used but are no longer considered directly useful for the assessment, and one case (northern anchovy) where the data were used for assessment, but the assessment is no longer being done. Another direct application of CalCOFI data in assessments is the sardine temperature control rule. Temperature data used in the Pacific sardine harvest control rule were originally taken from the Scripps Institution of Oceanography (SIO) pier. Reanalysis of the relationship between sardine recruitment and temperature showed that offshore temperature data from the CalCOFI survey should be used in the harvest control rule (Lindegren and Checkley, 2013). More recent work shows that there are methodological problems with the SIO pier temperature time series, emphasizing the need for the CalCOFI temperature data (Checkley and Lindegren, 2014).

The CalCOFI program serves a wide variety of marine research by collecting time series measurements on a repeatable, consistent basis. This benefits independent researchers, graduate students, government agencies, and the military, to name a few. Scientists around the world use all components of the CalCOFI time series, including hydrographic, mesozooplankton, and ichthyoplankton data and the more than 70,000 mesozooplankton samples curated by SIO to probe ecological processes and ocean climate of the CCS. For example, CalCOFI data were critical to the discovery that El Niño–Southern Oscillation (ENSO) cycles can have significant effects on ecosystems outside the tropics (Brinton, 1960; Berner, 1960; Chelton, et al., 1982). Brinton and Townsend (2003) extended these results by showing that euphausiid distributions respond not only to ENSO cycles but also to interdecadal climate cycles, such as the Pacific Decadal Oscillation (PDO). Di Lorenzo et al. (2008) used CalCOFI hydrographic data to show that the North Pacific Gyre Oscillation (NPGO) is a powerful predictor of changes in salinity, nutrients at depth, and chlorophyll-*a* in the CCS, illustrating that the system responds to multiple modes of climate variability. Over the last two decades, concentrations of oxygen at depth have been declining in the world ocean as well as in the CCS (Bograd et al, 2008), a phenomenon that may be linked to global climate change. However, McClatchie et al. (2010), drawing on the 60-year time series of oxygen in the Southern California Bight, show that the low oxygen concentrations observed today are not unprecedented; similar values were observed during the 1950s, suggesting that today's low concentrations of oxygen at depth are within the natural variability. Decadal trends in ichthyoplankton assemblages were discovered using species abundances from CalCOFI surveys spanning 1951–2008 (Koslow et al., 2013). Such trends have implications for the development of ecosystem-based management. Soutar and Isaacs (1974) enumerated fish scales in the laminated sediments of the Santa Barbara Basin to identify a ~ 60 year quasi-periodic fluctuation in the abundances of Pacific sardine and northern anchovy. This was not only a major achievement in our understanding of the ecology of these fishes but also a reminder that CalCOFI is both a seagoing program collecting data and a community of scientists using a wide range of approaches to understand the ecosystem

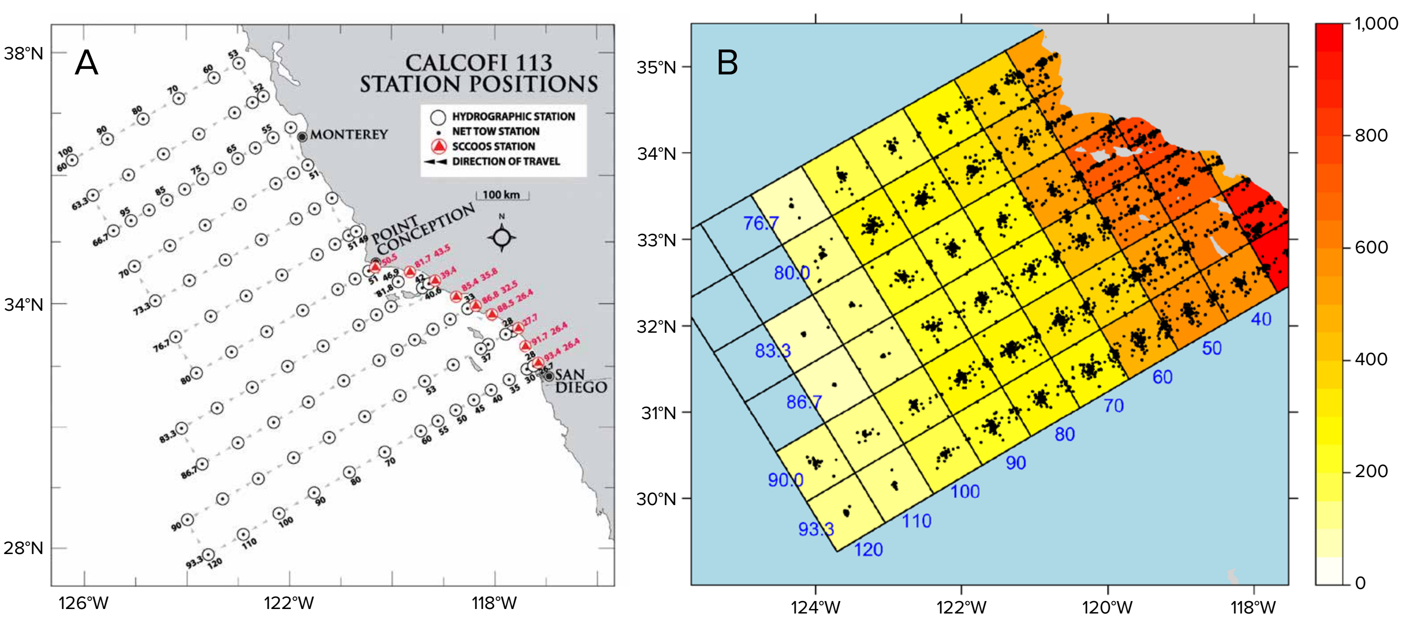

FIGURE 1. (A) One hundred thirteen-station California Cooperative Oceanic Fisheries Investigations (CalCOFI) pattern showing both the inshore Southern California Coastal Ocean Observing System (SCCOOS) stations and the northward extension of the core CalCOFI pattern to San Francisco that is generally sampled in winter and spring. The core CalCOFI pattern comprises the southernmost six lines and is sampled quarterly. (B) Grid pattern of 3.3-line by 10 station cells in the core CalCOFI sampling area. Color key indicates the actual number of sorted oblique bongo net samples collected within each cell for the period 1951–2010. Black dots indicate the actual sample locations.

of the CCS. Additional projects that have profited from the CalCOFI program are extensive and too numerous to list. In turn, these projects have been an asset to CalCOFI.

The core CalCOFI ichthyoplankton and hydrographic data, metadata, and relevant documentation are now served online through the US National Oceanic and Atmospheric Administration (NOAA ERDDAP[1], http://coastwatch.pfeg.noaa.gov/erddap/search/index.html?searchFor=calcofi). The data are derived from the entire 1950–present CalCOFI ichthyoplankton (all 450+ species) and zooplankton volume and hydrographic databases, which are managed by both NOAA's Southwest Fisheries Science Center (SWFSC) and SIO. There is up to a one-year lag due to sample processing. Continuous, Underway Fish Egg Sampler (CUFES) data will be served through ERDDAP in the near future. CalCOFI data are accessible either through a graphical user interface or from analysis programs (such as R or Matlab) using an OPeNDAP-type protocol. The data are available in a variety of output formats for download. The availability of the full 65-year core CalCOFI data through ERDDAP is a unique feature among long-term fisheries oceanography surveys.

Data generated by the CC-LTER and associated programs are available through the SIO Datazoo facility (http://oceaninformatics.ucsd.edu/datazoo), but may require approved access privileges. These data include particulate organic carbon (POC), dissolved organic carbon (DOC), chlorophyll size distribution, accessory photosynthetic pigments, flow-cytometric and microscopic enumeration of bacteria and microplankton, zooplankton species, krill species and stages, mesopelagic fish from trawls, and seabird and mammal counts.

Rockfish Recruitment and Ecosystem Assessment Survey (RREAS)

Since 1983, the SWFSC runs an annual midwater trawl survey to assess the abundance of young-of-the-year (YOY) rockfish and other groundfish in the California Current in an effort to help predict strong year classes in stock assessments and to better understand the oceanographic processes leading to strong recruitment (Ralston et al., 2013). The survey was expanded from its core area off the coast of central California in 2004 to encompass the region from the US-Mexico border to Cape Mendocino (Sakuma et al., 2006; Ralston and Stewart, 2013). Effort is focused on late spring (May and early June), the period of highest abundance for winter-spawning rockfishes (*Sebastes*) (Ralston et al., 2013). Most core area stations (Figure 2) are occupied three times every year, while most expanded area stations are occupied twice, in an effort to account for short term temporal variation in pelagic juvenile rockfish abundance. Since 1987, the survey has included routine oceanographic measurements (Ralston et al., 2013), as well as seabird and marine mammal observations during most daytime transits (Santora et al., 2011).

Off central and southern California, RREAS survey data on YOY rockfish and other groundfish abundance have been incorporated into stock assessments of winter-spawning commercially important *Sebastes* (He et al., 2011; Field, 2013). Historically, the stock assessment for Pacific hake (*Merluccius productus*) fitted indices of incoming year class strength. Other commonly encountered YOY groundfish include Pacific sanddab (*Citharichthys sordidus*), speckled sanddab (*C. stigmaeus*), lingcod (*Ophiodon elongatus*), and rex sole (*Glyptocephalus zachirus*); these species have either not been assessed or recruitment indices have not been developed for assessments, but these species do show covariation over time with other components of the ecosystem (Ralston et al., in press). The intent of such indicators is to better predict the episodic recruitment events that characterize many of these populations and lead to substantial shifts in abundance and catch rates in commercial and recreational fisheries (Field et al., 2010b). Expansion of the survey to southern California followed recognition that indices failed to adequately predict the magnitude of the 1999 year class (Hastie and Ralston, 2007; Ralston and Stewart, 2013). Recent analyses confirmed that while recruitment indices from the survey are significantly related to year class strength inferred by later age and length compositional data used in stock assessments for a number of rockfish species, the core survey area (sampled since 1983)

Sam McClatchie (sam.mcclatchie@noaa.gov) is Supervisory Research Oceanographer, Southwest Fisheries Science Center (SWFSC), National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS), La Jolla, CA, USA. **Janet Duffy-Anderson** is Supervisory Research Fisheries Biologist, Alaska Fisheries Science Center, NOAA, NMFS, Seattle, WA, USA. **John C. Field** is Supervisory Research Fisheries Biologist, SWFSC, NOAA, NMFS, Santa Cruz, CA, USA. **Ralf Goericke** is Researcher, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA, USA. **Dave Griffith** is Supervisory Research Fisheries Biologist, SWFSC, NOAA, NMFS, La Jolla, CA, USA. **David S. Hanisko** is Research Fisheries Biologist, Southeast Fisheries Science Center (SEFSC), NOAA, NMFS, Pascagoula, MS, USA. **Jonathan A. Hare** is Supervisory Research Oceanographer, Northeast Fisheries Science Center, NOAA, NMFS, Narragansett, RI, USA. **Joanne Lyczkowski-Shultz** is Research Fisheries Biologist, SEFSC, NOAA, NMFS, Pascagoula, MS, USA. **William T. Peterson** is Oceanographer and Senior Scientist, Northwest Fisheries Science Center, Hatfield Marine Science Center, NOAA, NMFS, Newport, OR, USA. **William Watson** is Supervisory Research Fisheries Biologist, SWFSC, NOAA, NMFS, La Jolla, CA, USA. **Edward D. Weber** is Research Fisheries Biologist, SWFSC, NOAA, NMFS, La Jolla, CA, USA. **Glenn Zapfe** is Research Fisheries Biologist, SEFSC, NOAA, NMFS, Pascagoula, MS, USA.

[1] ERDDAP is a data server that provides a simple, consistent way to download subsets of scientific data sets in common file formats and to make graphs and maps.

likely provides inadequate spatial coverage for many species with broader distributions (Ralston et al., 2013).

RREAS supports process and ecosystem studies, particularly with respect to the physical drivers of recruitment variability in groundfish populations and the role of spatial and temporal variability in juvenile groundfish and micronekton abundance. For example, hydrographic data from the survey were used to relate thermal fronts to YOY rockfish abundance and distribution (Sakuma et al., 2013). Hydrography was also correlated with changes in species composition and abundance of the epipelagic forage assemblage (Ralston et al., in press). The abundance of YOY rockfish and other forage such as Pacific sanddab (*Citharichthys sordidus*) and krill have long been linked to the breeding success and productivity of seabirds and salmon (Ainley et al., 1993; Thayer and Sydeman, 2007; Field et al., 2010a; Santora et al., 2014; Wells et al., 2012; Thayer et al., 2014). Finally, both physical and biological data from this survey are being used to evaluate the ability of a Regional Ocean Modeling System (ROMS) model to capture the spatiotemporal variability during winter and spring that affects year-to-year variability in the abundance and distribution of krill and juvenile rockfish (Schroeder et al., 2014).

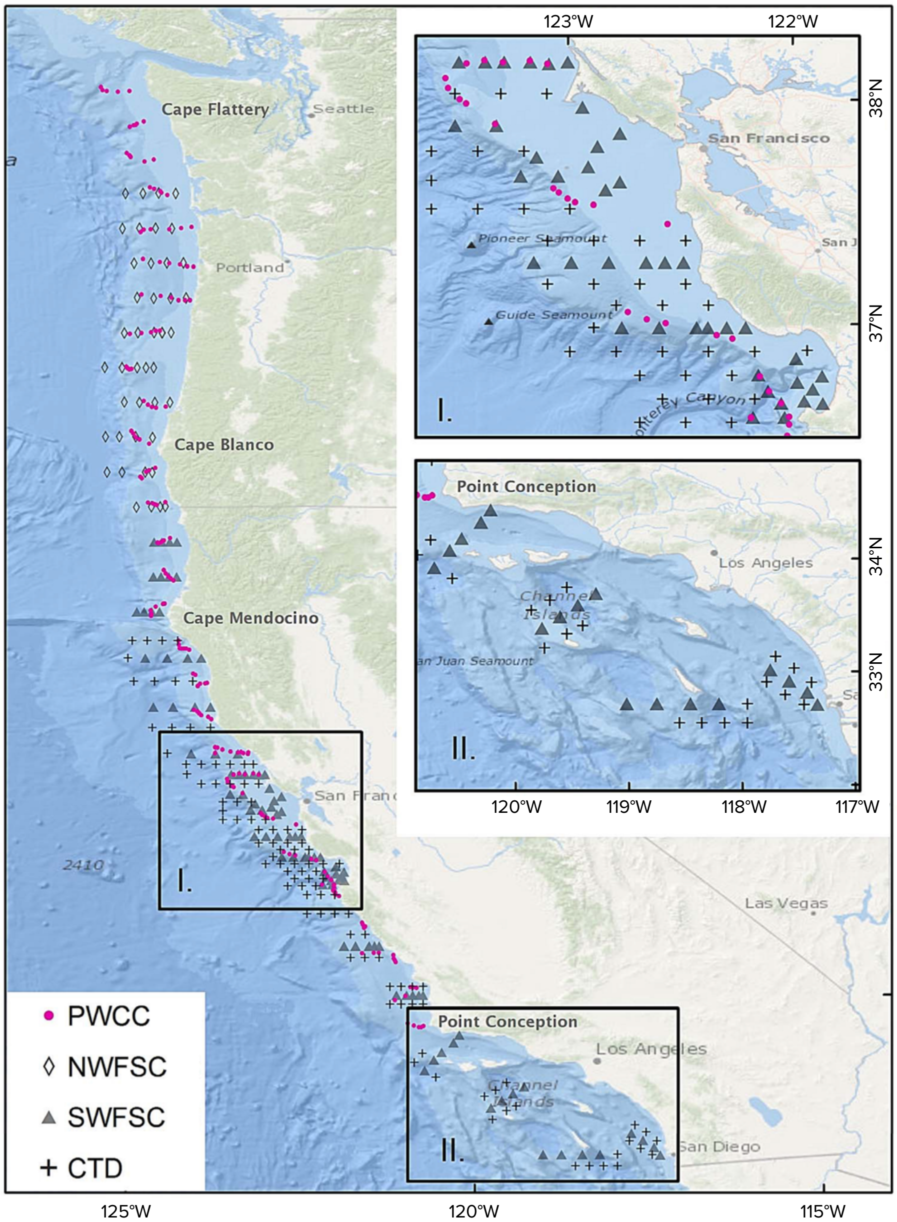

FIGURE 2. Trawl/CTD station and CTD-only station maps for the Rockfish Recruitment and Ecosystem Assessment Survey (RREAS). The core survey area stations located in the first inset box have been sampled continuously since 1983 (through 2014, and ongoing). The other Southwest Fisheries Science Center (SWFSC) stations in the expanded (Mendocino to Mexico) survey area have been sampled continuously since 2004 (excluding 2011), the PWCC stations were sampled (without conductivity-temperature-depth [CTD] data) from 2001–2009, and the Northwest Fisheries Science Center (NWFSC) stations off of Oregon and Washington have been sampled in 2011, 2013, and 2014 only.

RREAS environmental data (CTD cast data) are served on the ERDDAP website. Biological data reside in an SQL relational database that is not yet available online, but data are typically available upon request, and over 150 requests for biological data have been filled since 2002. Summary results are included in summary reports (such as the State of the California Current and the California Current Integrated Environmental Assessment [IEA]).

Newport Hydrographic Line

Since 1996, the rationale for the Newport line that crosses the shelf off Oregon (44.6°N) was to provide a set of climate, oceanographic, and ecological indicators that describe "ocean conditions" in an ecosystem context. These data are used to produce advice on ocean conditions for salmon managers and others interested in how variable ocean conditions affect fish and fisheries. The Newport Hydrographic (NH) Line (Figure 3) was first sampled by physical oceanographers from Oregon State University from 1961–1973. Zooplankton and krill were sampled from 1963–1968, and ichthyoplankton were added for the period 1969–1973. A hiatus followed, with very little systematic sampling until 1996. Since then, the inner 40 km of the Newport line has been sampled on a fortnightly basis while the more offshore parts of the line (out to 140 km from shore) were sampled quarterly from 1998–2005, and two to three times per year since 2005 (Figure 3). The data collected since 1996 include CTD and oxygen profiles, Secchi disk depths, nutrients, chlorophyll, and plankton net tows for copepods, krill, pteropods, and ichthyoplankton. The NH data set is unique in terms of its frequency of data collection (fortnightly throughout the year) and its emphasis on obtaining species abundance data (rather than broad taxonomic groupings or the volume of zooplankton in a sample), allowing analysis of effects of physical forcing on food-chain structure and ecosystem dynamics. Another defining feature of the NH work is that the CTD casts and zooplankton net tows are processed within a few days of collection, which allows tracking changes in ocean conditions in near-real time.

Data from the NH line time series allows description of differences in local ocean conditions in terms of changes in basin-scale forcing (PDO and ENSO), the nature of the source waters that feed the northern California Current, and regional forcing (upwelling), as well as local response in terms of water properties (temperature, salinity, and oxygen), chlorophyll, and copepod and ichthyoplankton species abundance and composition. Analysis of relationships between oceanographic and ecological indicators and salmon survival is through statistical models and simple bivariate correlations, for example, between salmon returns and the PDO, or between the biomass of copepods and winter abundance of those ichthyoplankton species that become the forage base for salmonids in the spring and summer (Peterson and Schwing, 2003; Daly et al., 2013). Principal components analysis (Peterson et al., 2013) and maximum covariance analysis (Burke et al., 2013) of the 16 indicators have also been used to produce aggregated indicators of ecosystem state. Annual outlooks are provided on salmon one to two years in advance of their return to their natal streams (and entry into the fishery). The data and "outlooks" are used by Washington and Oregon state and tribe salmon managers, by Oregon's Watershed councils, and by NOAA's National Marine Fisheries Service (NMFS) Regional Office to monitor salmon returns to the Columbia River as well as coastal rivers. The website is popular among sports fishermen who read it to get a feel for the probability of good versus poor catches in a given year. Because the NH Line is the only regularly sampled hydrographic *and* plankton line in the Pacific Northwest, when combined with data from related efforts associated with marine laboratories (located at Trinidad, Bodega Bay, and Monterey Bay, CA) and, of course, from CalCOFI and Investigaciones Mexicanas de la Corriente de California (IMECOCAL), one can obtain a view of the status of the entire California Current. This is done regularly in the annual "State of the California Current" document published as part of the CalCOFI Reports series (Bjorkstedt et al., 2012), in the California Current Integrated Ecosystem Assessments (http://www.noaa.gov/iea/regions/california-current-region), in the "State of the Pacific Ocean" report prepared annually by our Canadian colleagues at Department of Fisheries and Oceans (http://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2013/2013_028-eng.pdf), and in the North Pacific Marine Science Organization (PICES) bi-annual report "Marine Ecosystems of the North Pacific" (https://www.pices.int/publications/special_publications/NPESR/2010/NPESR_2010.aspx). Brief notes of significant changes in the California Current are also posted in the "Western Regional Quarterly Climate Impacts and Outlooks" report (http://www.drought.gov/drought/content/resources/reports). Data from CalCOFI and RREAS are also published

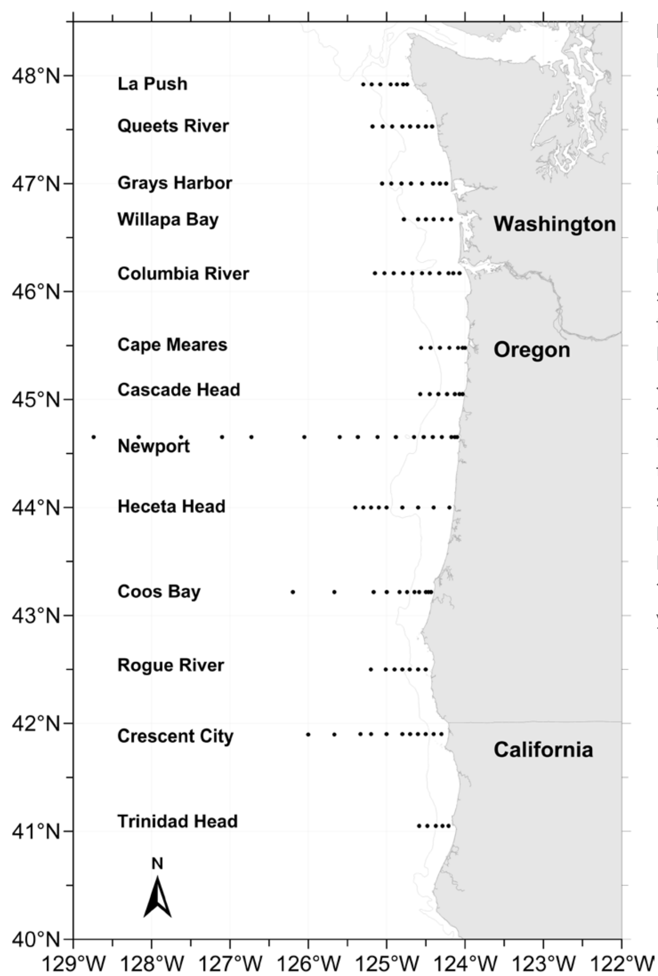

FIGURE 3. Chart showing location of transects and stations for which hydrographic and plankton data are available for study of latitudinal variations in diversity of copepods and krill. The Newport Hydrographic Line has been sampled biweekly since 1996; transects and stations to the north of Newport have been sampled in May, June, and September since 1998 and include pelagic fish trawls (Nordic 265 Trawl); transects and stations to the south of Newport were sampled quarterly for hydrography and zooplankton from 1998 to 2005, but twice per year since.

in these reports.

A key finding from data on abundance and biomass of copepod species is that two general types of copepods occur along the Oregon coast—"cold water sub-Arctic species" and "warm water subtropical species." Climatologically, the cold water group dominates during summer when the inner branch of the California Current (CC) is fed by southward flowing sub-Arctic water, and the warm water group dominates in winter when the inner branch of the CC flows northward as the Davidson Current. Interannual variations in this pattern are related to the sign (positive or negative) of the PDO. When the PDO is in negative phase, cold water species have positive abundance and biomass anomalies, but when the PDO is in positive phase (and/or during El Niño events), warm water species have positive anomalies regardless of season. The significance of this result is that the cold water copepod species have relatively high concentration of lipids whereas the warm water species do not (Hooff and Peterson, 2006; Lee et al. 2006); thus, the base of the pelagic food chain in the coastal upwelling zone off Oregon has very different bioenergetic and nutritional content, depending on the phase of the PDO.

Salmon landings in the Gulf of Alaska and the Bering Sea increase during years when the PDO is in positive phase but decrease when the PDO is negative, whereas returns of salmon to rivers of the Pacific Northwest are highest (lowest) when the PDO is in negative (positive) phase (Mantua et al., 1997). Francis and Hare (1994) noted that the ecosystem response during those years when change-points were observed was pronounced and occurred in the year of the change, leading them to suggest that the processes controlling salmon production were acting during their first summer at sea. We propose that the reason why the abundance of species such as salmon change so quickly is because the bioenergetics content of their forage base (juvenile pelagic fish and euphausiids) changes rapidly due to a switch from lipid-rich cold water copepods to lipid-poor warm water copepods that occurs nearly in lockstep with the changes in sign of the PDO. The mechanisms linking the PDO with copepods (and ultimately salmon) are transport processes that control the source waters feeding the salmon-rich northern California Current. Both Keister et al. (2011) and Bi et al. (2011) show that transport is linked with the PDO such that in negative PDO phase, a greater proportion of the water entering the CC is from the coastal Gulf of Alaska and sub-Arctic side of the North Pacific Current, where lipid-rich copepods dominate, whereas in positive PDO phase, a greater proportion of the water is from the subtropical branch of the North Pacific Current where lipid-poor copepods dominate.

Although the International Panel on Climate Change (IPCC)-class models provide an important tool for predicting changes in the physical environment, capturing the statistics of the decadal climate modes (PDO, NPGO, and ENSO), they are only beginning to capture mesoscale and upwelling variability in the CC. Thus, in the near term, in situ observations such as those provided by CalCOFI, RREAS, Newport line, and other observational programs will continue to be our chief source of data and understanding on long-term changes in the California Current Ecosystem. The survey data are essential for validating ROMS, Global Circulation Model, and climate models.

NH line copepod data are available on request, and graphical summaries are available through the Scientific Committee on Research (SCOR) Working Group 125 website (http://www.st.nmfs.noaa.gov/plankton/metabase/us-000005) as well as through the "copepod" website (http://www.st.nmfs.noaa.gov/plankton/time-series). Graphical summaries of the data used to produce salmon forecasts (including the copepod and ichthyoplankton indices) are available at http://www.nwfsc.noaa.gov by clicking on "Salmon Forecasts."

Recruitment Processes Program (EcoFOCI)

Field sampling by the NOAA Alaska Fisheries Science Center (AFSC) Recruitment Processes Program (Fisheries Oceanography and Coordinated Investigations, FOCI, now EcoFOCI, see Sheffield Guy at al., 2014, in this issue) in the Gulf of Alaska prior to 1984 primarily consisted of small-scale, process-oriented studies in the vicinity of Kodiak Island. Since then, the primary objective of Gulf of Alaska sampling has been to sample the offspring of a major spawning population of walleye pollock in Shelikof Strait. Ichthyoplankton are consistently sampled over a fixed area (Figures 4 and 5) near the peak occurrence of the larvae of walleye pollock and a variety of other taxa, with ancillary collection of oceanographic data. Surveys for YOY pollock downcurrent of larval surveys have occurred since the late 1990s. YOY pollock surveys also provide information on key forage fishes, including capelin (*Mallotus villosus*) and eulachon (*Thaleichthys pacificus)* in the Gulf of Alaska.

Periodic collections of ichthyoplankton in the Bering Sea began in the 1970s, with systematic collections beginning in the 1990s. EcoFOCI routinely samples the southeastern Bering Sea shelf from the Alaska Peninsula to north of the Pribilof Islands (Figures 4 and 5), which encompasses the main spawning areas for walleye pollock and Pacific cod (*Gadus macrocephalus*). Process-oriented research on YOY pollock has occurred since the 1990s, but surveys have been conducted over a systematic grid since the mid-2000s in collaboration with NOAA's Ecosystems Monitoring and Assessment program.

The Alaskan EcoFOCI data have been utilized by researchers to examine long-term effects of environmental forcing on fish community structure and organization, shifts in fish recruitment dynamics, and interannual and decadal variations in distribution, abundance, and size structure (Doyle et al., 2009; Duffy-Anderson et al., 2006; Dougherty et al., 2007; Siddon et al., 2011; Doyle and Mier, 2012). Larval walleye pollock data provide an early predictor of recruitment strength in the Gulf of Alaska (Megrey et al., 1996), supplementing data derived from hydroacoustic and bottom trawl surveys to inform management. In addition, fishery-independent estimates of spawning stock biomass of walleye pollock in the Gulf of Alaska can be derived from egg data collected on annual ichthyoplankton surveys (Picquelle and Megrey, 1993), which complement acoustic surveys of adult spawning biomass (Jones et al., 2014).

Several studies have used AFSC larval time series data to show that larval communities are timely indicators of environmental change, displaying the effects of variations in local and broad-scale environmental forcing (Duffy-Anderson et al., 2006; Boeing and Duffy-Anderson, 2008; Busby et al., 2014), well before changes are manifested at higher trophic levels. Early detection of ecosystem phase shifts provides tools to help plan, mitigate, and remediate impacts of environmental variability. EcoFOCI larval data have also been key to documenting climate-mediated shifts in spatial spawning distributions of adult walleye pollock in the Gulf of Alaska (Bacheler et al., 2010) and the Bering Sea (Petrik et al., in press), as well as showing that phenological shifts in walleye pollock spawning may occur in response to thermal variations (Smart et al., 2012).

Data derived from EcoFOCI YOY walleye pollock surveys in the Gulf of Alaska have contributed to improved understanding of mesoscale patterns in spatial production (Wilson, 2009), trophic interactions (Bailey, 2000; Ciannelli et al., 2005), and the development of forecast models of fish production. For example, Bailey et al. (2005) developed a nonparametric statistical recruitment forecast model that included the nonadditive and nonlinear effects of environmental variables. Their method captured the patterns and trends in walleye pollock recruitment and demonstrated the utility of hybrid models that include both density-dependent and density-independent variables in recruitment prediction. Further, time series data have been incorporated into both biophysical and trophic models to reveal information on connectivity, production, spatiotemporal variability, and population structure.

The EcoFOCI walleye pollock larval and YOY time series are the first indicators of year-class strength of the incoming cohort in the Gulf of Alaska. Recent indices of distribution and abundance of walleye pollock juveniles have been a "hot topic," signaling the apparent large size of the 2013 year-class in the AFSC's annual Ecosystem Status and Trends report (Zador, 2013) that summarizes ecosystem information for the North Pacific Fishery Management Council, scientific stakeholders, and the public. In addition, the Gulf of Alaska larval time series is used to provide estimates of annual larval abundance in a historical context for a variety of other species, including Pacific halibut (*Hippoglossus stenolepis*), Pacific cod, arrowtooth flounder (*Atheresthes stomias*), and rockfishes, among others.

The most robust EcoFOCI ichthyoplankton raw data (bongo, neuston) are available through the Ichthyoplankton Information System (IIS), a searchable, online portal hosted by the Alaska Fisheries Science Center (http://access.afsc.noaa.gov/ichthyo). These data, and other data from less frequently used

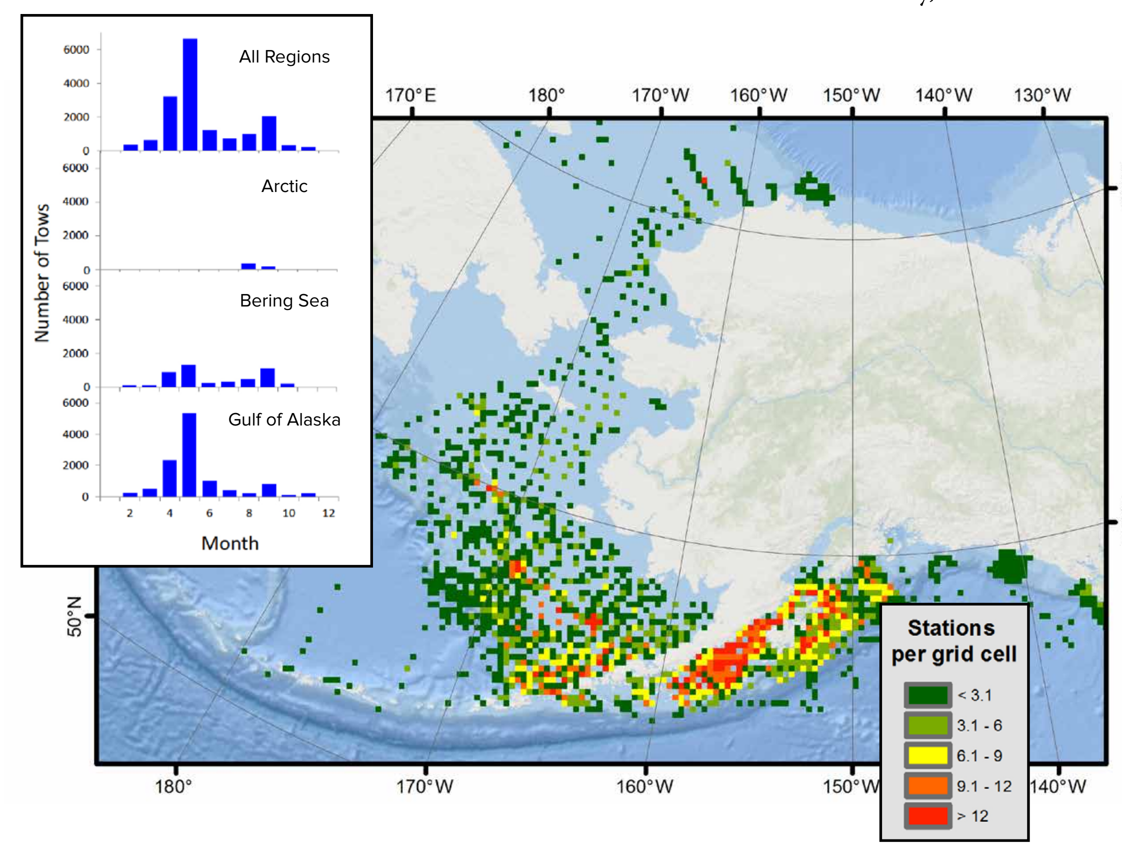

FIGURE 4. Map of historical ichthyoplankton sampling for EcoFOCI (Ecosystems & Fisheries-Oceanography Coordinated Investigations) using Tucker and bongo nets in the Gulf of Alaska and the Bering, Chukchi, and Beaufort Seas (1972–present). Squares denote 20 x 20 km geographic areas. Color ramp denotes frequency of sampling. Histogram indicates sampling effort by month.

sampling gears, are also retained in a relational Oracle database (EcoDAAT) at the AFSC and are available upon request. The online IIS serves a cross section of user needs. Primarily, it is a taxonomic guide that can be used to identify North Pacific fish eggs and larvae by providing information on meristics, morphometrics, and developmental characteristics. It also provides synoptic information on distribution, abundance, and seasonality of eggs and larvae over the North Pacific, Gulf of Alaska, Bering Sea, and, most recently, in the Chukchi and Beaufort Seas. The IIS allows users to access historical larval time series raw catch data (catch per unit area) from 1972 to near present. Links to metadata, program information, and points of contact are available on the website. A catalog of research cruises and objectives can be found at: http://access.afsc.noaa.gov/icc/index.php. Associated EcoFOCI raw physical data are available through the National Oceanographic Data Center (NODC) at http://www.nodc.noaa.gov/access. Limited concurrently collected zooplankton displacement volume data are available at http://www.st.nmfs.noaa.gov/copepod, and work continues to make more data available.

Ecosystem Monitoring Program (EcoMon)

The current objectives of the Northeast Fisheries Science Center (NEFSC) fisheries oceanography survey programs are to monitor the pelagic components of the Northeast US Shelf Large Marine Ecosystem that are relevant to living marine resources and to index the seasonal, annual, and decadal changes in the ecosystem conditions. These surveys built upon earlier work that emphasized the critical role of understanding the ecosystem in managing living marine resources in the region (Bigelow, 1926; Sette, 1943; Clarke et al., 1946). The NEFSC has been conducting systematic oceanographic surveys on the Northeast US Shelf since the early 1960s (Figure 6). Though conducted under the auspices of different programs with varying objectives and focal areas, these surveys have all used the same sampling approach, resulting in a more than 40-year time series of hydrographic and lower-trophic-level measurements (Richardson et al., 2010).

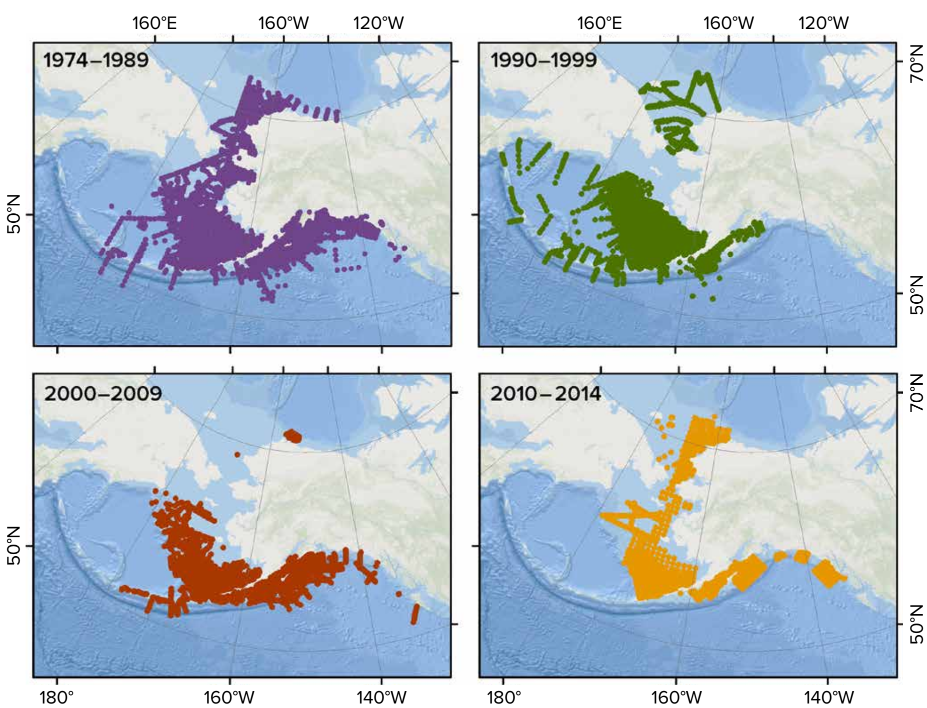

FIGURE 5. Maps of EcoFOCI historical physical sampling (1974–present) in the Gulf of Alaska and the Bering, Chukchi, and Beaufort Seas by decade. Note that physical sampling in the Arctic (Chukchi and Beaufort Seas) was robust until 2000, followed by reduced effort for nearly a decade, and reinvigorated effort beginning in 2010.

The first component of NEFSC oceanographic surveys was a Continuous Plankton Recorder (CPR) operation that began in 1963 (NEFSC Ship of Opportunity Program [SOOP]; Jossi et al., 2003) and represented the longest plankton time series in the Northwest Atlantic Ocean. Hydrographic sampling was conducted in collaboration with the NOAA Atlantic Oceanographic and Meteorological Laboratory, and monthly transects were sampled across the Gulf of Maine and the Mid-Atlantic Bight, complemented by transects across the southern flank of Georges Bank and in Canadian waters. Although the NEFSC ended its participation in CPR surveys in 2013, the Sir Alister Hardy Foundation for Ocean Science is attempting to step in and continue the CPR transects.

A second component of the NEFSC oceanographic surveys is plankton sampling from research vessels. Systematic sampling began in 1971 in the northern part of the Northeast US Shelf ecosystem during fall and winter. Full-shelf, year-round plankton sampling began with the Marine Resources Monitoring and Prediction (MARMAP) program (1977–1987) and continues today as the EcoMon program (1999–present). Through 2012, EcoMon surveys were conducted six times per year from Cape Hatteras, North Carolina, to Nova Scotia, Canada: four surveys were dedicated cruises and two were piggybacked on the NEFSC fall and spring trawl surveys. Approximately 120 plankton stations are occupied on each survey. In 2013 and 2014, dedicated surveys were cut to two, decreasing the seasonal coverage of the shelf. The same sampling gear has been used since the early 1970s. More than 25,000 plankton stations have been occupied, and most of the samples have been sorted and identified. Kane (2007) describes the zooplankton samples and Richardson et al. (2010) describe the ichthyoplankton samples.

A third component of the NEFSC

oceanographic surveys is hydrographic sampling (salinity, temperature, and density). Hydrographic measurements are made on most NEFSC resource surveys (e.g., plankton, scallop, trawl, and marine mammal surveys). Data collection began systematically on the NEFSC fall and spring trawl survey cruises in the 1960s. With the start of the MARMAP program in 1977, temperature and salinity measurements were made at fixed depths with water bottles. Since the mid-1990s, CTDs have been used. These large-scale surveys have been integrated with other programs (Global Ocean Ecosystem Dynamics [GLOBEC], NASA Climate Variability on the East Coast [CliVEC], NOAA Ocean Acidification, Bureau of Ocean Energy Management) to supplement the NEFSC oceanographic survey objectives and to provide additional information for these other programs. The integration of additional projects and sampling has led to the concept of an integrated pelagic survey (IPS) of the pelagic components of the Northeast US Shelf ecosystem from chemistry to seabirds and marine mammals. The purpose of the IPS is to quantify forage fish, marine mammals, and seabirds in combination with the chemical, physical, and other biological components of the ecosystem.

Data from EcoMon are used in regional, national, and international products. Long time series from the CPR transect across the Gulf of Maine, combined with large-scale oceanographic data and climate indices, allowed elucidation of the effects of Arctic winds and currents on Northeast Atlantic salinity, nutrients, and zooplankton production (Greene et al., 2008, 2013). Overall, it is broadly recognized that a long-term oceanographic data set (chemical, physical, and biological) is a required component of ecosystem-based fisheries management, protected species management, and climate change adaptation.

With regard to fisheries management, the data have provided context for stock assessments for decades, including stock distribution (Murawski, 1993), identification (Begg et al., 1999), and productivity (Mountain and Kane, 2009) as well as essential fish habitat designation (Lough, 2004). More recently, data from NEFSC oceanographic surveys have been used directly in stock assessments, both as contextual information and in the models. Larval indices were developed following Richardson et al. (2010) as an additional measure of spawning stock biomass; these indices provide context for some stock assessments (e.g., Atlantic herring, *Clupea harengus*, and Atlantic mackerel, *Scomber scombrus*) and are directly incorporated into others (e.g., yellowtail flounder, *Limanda ferruginea*). Zooplankton data have been used to incorporate information about prey species. These data are not incorporated directly into an assessment, but rather are used to examine potential changes in stock productivity (e.g., Atlantic herring). Hydrographic data can provide context to stock assessments (Brodziak and O'Brien, 2005) and have been used recently in environmentally explicit stock recruitment models of winter flounder (*Pseudopleuronectes americanus*) and in thermal niche models to estimate availability of butterfish (*Peprilus triacanthus*) to surveys.

The oceanographic survey data contribute to protected species assessment and management. Although marine mammal and sea turtle stock assessments do not use oceanographic survey data, there is strong evidence that oceanographic properties affect their distributions and

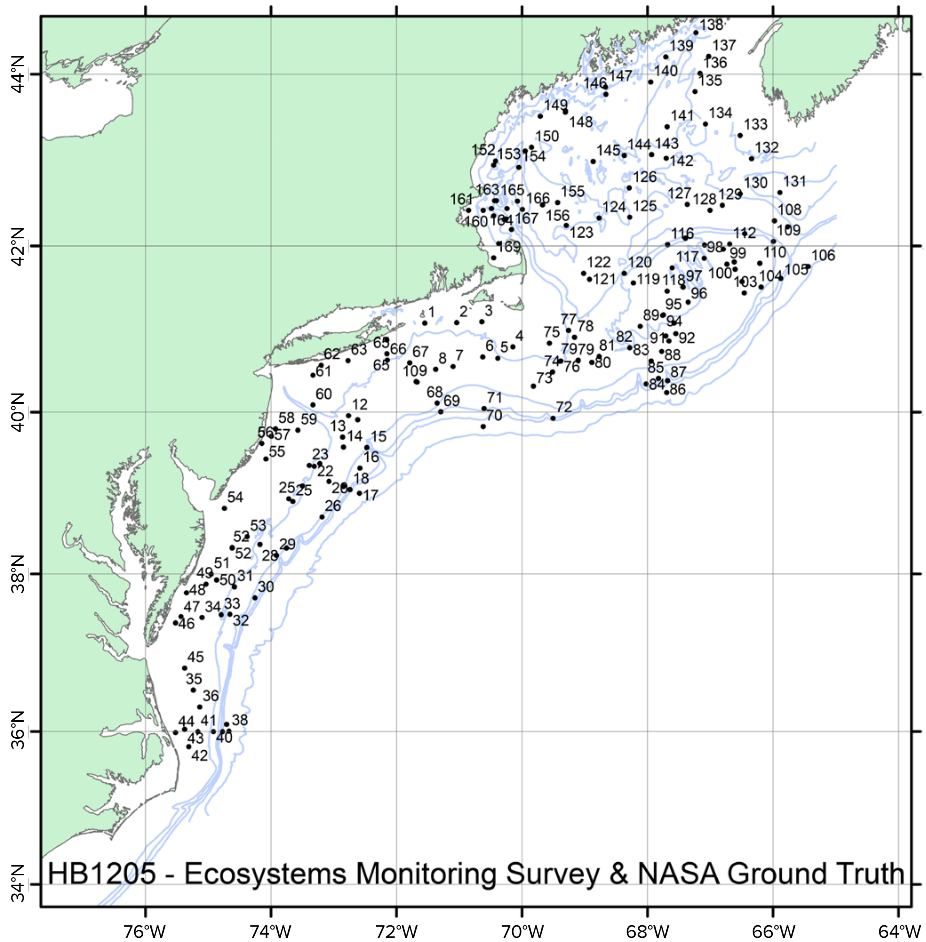

FIGURE 6. Locations of Ecosystem Monitoring Program (EcoMon) stations for a survey in August 2012. Stations are based on a random-stratified survey design, so every survey plan is different, but the general coverage and station density of a survey are the same. During the 1999–2012 period, this survey design was sampled six times per year to capture the pronounced seasonal systems in the ecosystem. Recent budget and ship time cuts have reduced the survey to four times per year, with priority given to the fall through spring period.

productivity in many regions, including the Northeast US Shelf (Braun-McNeill et al., 2008; Meyer-Gutbrod and Greene, 2014). Current activities include combining marine mammal and oceanographic surveys to improve understanding of marine mammal distribution in time and space. Additionally, a number of fish species are coming under consideration of the Endangered Species Act, and oceanographic survey data are contributing to listing decisions, status determinations, and other management actions regarding Atlantic salmon (*Salmo salar*), river herring (alewife, *Alosa pseudoharengus*), and blueback herring (*A. aestivalis*).

Numerous environmental impact statements and ecological site characterizations are also supported by NEFSC oceanographic surveys. Temperature and salinity data contribute to site descriptions. Zooplankton data contribute to an understanding of ecosystem structure and function. Ichthyoplankton data support adult equivalent modeling, which calculates loss of future fisheries production resulting from death of larvae by the proposed activities (Rago, 1984).

Finally, oceanographic survey data contribute to the nascent ecosystem and climate assessment activities in many regions. Ecosystem models have used zooplankton data to quantify lower-trophic-level production and temperature data to estimate temperature-dependent consumption rates (Link et al., 2009, 2010). These research models are currently in transition to provide strategic advice to fisheries management in the region. NEFSC oceanographic surveys also contribute to regional Ecosystem Status Reports (EcoAP, 2012) and Ecosystem Advisories (http://nefsc.noaa.gov/ecosys/advisory/current). These products provide historical and current information regarding the state of the ecosystem, which is used in the development of ecosystem-based management. Data are also used in International Council for the Exploration of the Sea assessments: one reporting on the past and current physical oceanographic conditions in the North Atlantic (Beszczynska-Möller and Dye, 2013) and another documenting the past and current state of zooplankton in the North Atlantic (O'Brien et al., 2013). These reports are used to support ecosystem-based management activities across the Atlantic and to understand the effects of past climate variability and change in the Atlantic. NEFSC oceanographic surveys contribute to evaluations of the effect of climate change on living marine resources in the ecosystem, including Atlantic cod (*Gadus morhua*; Fogarty et al., 2008), cusk (*Brosme brosme*; Hare et al., 2012), and river herring (Lynch et al., 2014). More general studies include changes in fish distributions over time (Nye et al., 2009) and changes in fish productivity (Bell et al., 2014). These specific studies contribute to an overall Fisheries Climate Vulnerability Assessment.

NEFSC EcoMon survey data are generally available, but availability is limited by historical data management practices; initially, zooplankton, ichthyoplankton, and hydrographic data were collected by separate groups and stored in separate databases. Further, zooplankton collected with the CPR were stored separately from zooplankton collected with the bongo net. In many cases, data collected in the same operation ended up in multiple unlinked databases; although progress is being made, linking these databases remains a barrier today. Plankton data (for ichthyoplankton and zooplankton) and hydrographic data are now stored in modern Oracle databases. Current efforts involve linking these two databases so researchers and assessment scientists can take full advantage of coincident data. CPR data are stored in a MatLab structure, and, owing to end of the activity, no further improvements in data storage will be made by the NEFSC.

Much of the NEFSC oceanographic survey data is publicly available, but again, linking across data sets remains a problem. Hydrographic data are available through NODC and on an NEFSC server (http://www.nefsc.noaa.gov/epd/ocean/MainPage/ioos.html). Zooplankton data are available on a public ftp site (ftp://ftp.nefsc.noaa.gov/pub/dropoff/jhare/EcoMon_Data). Ichthyoplankton data are available upon request, and efforts are underway to make them available on a public ftp site similar to that for zooplankton data. CPR data are available on a public ftp site (ftp://ftp.nefsc.noaa.gov/pub/dropoff/jhare/EcoMon_Data). Efforts are underway to make the CPR data available through the US Integrated Ocean Observing System (IOOS). Much of the NEFSC oceanographic survey data is also available through the Biological and Chemical Oceanography Data Management Office (http://tw.rpi.edu/web/project/BCO-DMO). Much of the data collected by integrated programs (GLOBEC, CliVEC) is also available, but coupling with the broader NEFSC oceanographic survey data remains problematic. Coupled hydrographic and trawl survey data are available (http://www.nefsc.noaa.gov/epd/ocean/MainPage/ioos.html); this coupling is a result of the high priority of trawl surveys. Future efforts will see broader and more integrated availability of NEFSC oceanographic survey data.

Southeast Area Monitoring and Assessment Program (SEAMAP)

Fisheries oceanography surveys were initiated in the Gulf of Mexico (GOM) by the National Marine Fisheries Service in 1977 as part of MARMAP (Sherman et al., 1983; Richards, 1987). The success of those initial surveys in providing a useful fishery-independent index of the western Atlantic bluefin tuna (*Thunnus thynnus*) spawning stock furnished the motivation and justification for all subsequent plankton survey activities in the GOM. Plankton and environmental sampling during those early annual surveys (1977–1981) were conducted in open GOM waters in April and May using essentially the same plankton gear and methods used today. Modern instrumentation, however, is now used for environmental data collection. Starting in 1982, most resource surveys, including plankton surveys carried out by the NMFS/SEFSC/Mississippi Laboratories, were incorporated into SEAMAP (Sherman et al., 1983; Stuntz et al., 1983). Under this joint federal-state program coordinated through the Gulf States Marine Fisheries Commission, the SEFSC and the states of Louisiana, Mississippi, Alabama, and Florida cooperatively conduct plankton sampling during resource surveys in the GOM. This cooperation resulted in a time series of standardized, fisheries-independent data on the occurrence, abundance, geographical distribution, and pelagic habitat of the early life stages of fishes that are used to support assessment and management of key finfish species in the GOM.

The SEAMAP sampling domain, as originally defined, covers the northern GOM from the 10 m isobath out to the boundary of the US Exclusive Economic Zone (EEZ). Primary sampling is conducted at predetermined stations arranged in a fixed, systematic grid (Figure 7). Intermittent sampling outside the SEAMAP domain has been conducted in the southern GOM and, more recently, in the Caribbean Sea. Plankton sampling is carried out principally during three dedicated plankton surveys but is also piggybacked on three trawl surveys (Lyczkowski-Shultz and Hanisko, 2007). The number of sites occupied varies with the type of survey, but typically between 100 and 180 stations are sampled during each survey. Historically, seasonal coverage was limited to open Gulf waters in spring and shelf waters in summer and fall months with sporadic coverage in winter months (Lyczkowski-Shultz and Hanisko, 2007). Until recently, only the spring and late summer/early fall dedicated plankton surveys were conducted Gulf-wide. A change in sampling design in 2008 expanded the coverage of trawl surveys and led to Gulf-wide plankton sampling during the summer and fall trawl surveys (Rester, 2010). Starting in 2007, more consistent sampling in winter months was instituted with annual, dedicated winter plankton surveys spanning mid-shelf to open Gulf waters. Plankton gear and methodology used during SEAMAP surveys (Rester, 2010) are similar to those recommended by Kramer et al. (1972), Smith and Richardson (1977), and Posgay and Marak (1980). Since the inception of the SEAMAP program, most plankton samples are sorted for cephalopod early life stages, fish eggs, and fish larvae. Starting in 2003, decapod crustacean larvae and other major invertebrate zooplankton taxa were added to analysis protocols for identification and enumeration in select SEAMAP samples. These new data on the invertebrate zooplankton component provide much needed information on lower trophic levels from which a broader perspective of the Gulf ecosystem can be gained.

SEAMAP ichthyoplankton data are used to generate fishery-independent indices of relative abundance that are used in the assessment of a number of important species in the GOM, including Atlantic bluefin tuna (Scott et al., 1993; Muhling et al., 2010), skipjack tuna (*Katsuwonus pelamis*), red snapper (*Lutjanus campechanus*), and king mackerel (*Scomberomorus cavalla*) (Hanisko

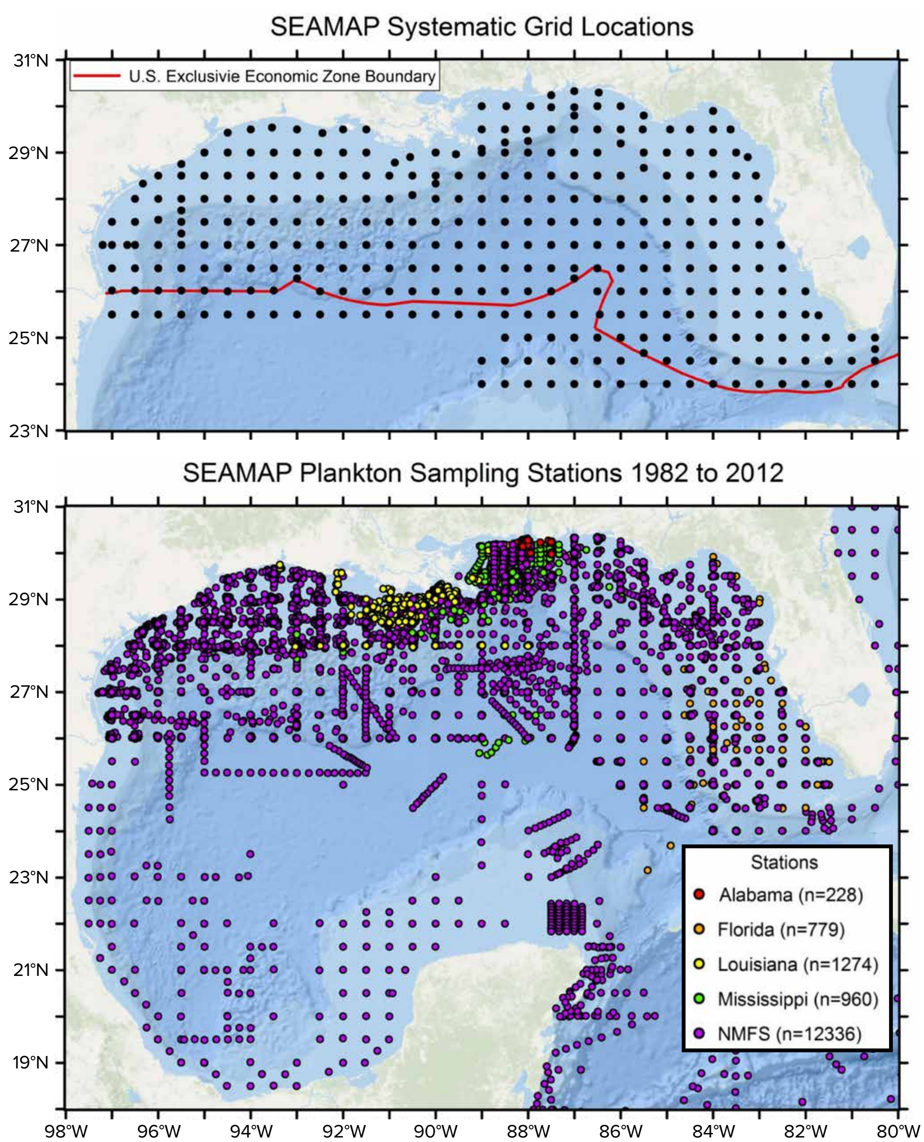

FIGURE 7. Locations of SEAMAP (Southeast Area Monitoring and Assessment Program) systematic grid stations across the northern Gulf of Mexico (top) and the stations that were occupied during fishery oceanography surveys from 1982 to 2012 (bottom). Over 43,500 standard plankton samples were collected during that time period.

et al., 2007; Gledhill and Lyczkowski-Shultz, 2000). Similar indices have been considered for vermilion snapper (*Rhomboplites aurorubens*), gray triggerfish (*Balistes capriscus*), and Gulf menhaden (*Brevoortia patronus*).

Nonfisheries applications of SEAMAP fisheries oceanographic survey data run the gamut, from classical descriptions of larval development to environmental impact assessments to monitoring changes in the Gulf ecosystem. This latter application has become more valuable with the growing recognition of the influence of local, regional, and global atmospheric/ocean coupling. Specimens generated by SEAMAP surveys provided material for the first major regional identification guide to larval fishes in the western central North Atlantic (Richards, 2006). More recently, SEAMAP samples provided specimens for a major contribution to identification of portunid (swimming) crab larvae in the GOM (Knight, 2014).

Ichthyoplankton data from the SEAMAP time series were used to quantify the potential impact of entrainment mortality by liquefied natural gas facilities and to estimate forgone fisheries production (Gallaway et al., 2007). The value of SEAMAP plankton data, for both fish and decapods, in resource damage assessment was universally recognized during the 2010 Deepwater Horizon oil spill when the SEAMAP plankton database provided crucial information on the potential harm to fish eggs and larvae in the path of the oil spill (Muhling et al., 2012b). These data are the primary source of pre-spill, historical data for use in damage assessment models.

The SEAMAP survey data were the basis for a characterization of ichthyoplankton in specialized Gulf habitats/habitat areas of particular concern in the northeastern GOM (Lyczkowski-Shultz et al., 2013). The distribution of reef fish larvae from open Gulf surveys in relation to oceanographic features (i.e., Loop Current and associated eddies) as interpolated from satellite images supported an investigation of potential "sources" and "sinks" of larval recruits (Hanisko and Lyczkowski-Shultz, 2003). Zooplankton communities have been delineated in the context of fishery management zones from analysis of SEAMAP CUFES samples (Millett, 2010), and the first-ever analysis of the Gulf-wide distribution of portunid crab larvae was based on SEAMAP samples (Knight, 2014). Researchers have also used SEAMAP data to infer spawning seasonality and provide an alternate means of predicting and identifying locations of fish spawning and nursery habitats for a number of fishery managed species from genetically identified eggs collected in CUFES samples (Frank Hernandez, Gulf Coast Research Laboratory, *pers. comm.*, August 12, 2014).

Using a field of ocean currents developed from ocean observations and an operational model, Johnson et al. (2009) described potential pathways of larval red snapper advective transport between the western and eastern Gulf from location of captures during SEAMAP surveys. Results of this study indicated few red snapper larvae produced in the western GOM where the adult population is concentrated are transported to the eastern GOM (West Florida Shelf) where red snapper abundance is low. Prior to modern fishing vessels and methods, the population in the eastern GOM supported a large and profitable fishery.

In the recent integrated ecosystem assessment for the GOM, Karnauskas et al. (2013) suggested that the SEAMAP time series of net-caught zooplankton biomass as measured by plankton displacement volumes may provide a measure by which to monitor changes in the GOM ecosystem. Changes in abundance of larvae within select families of fishes over three decades of SEAMAP surveys also show potential as an indicator of ecosystem level shifts in ichthyofauna (Muhling et al., 2012a). From an examination of grouper larvae over three decades of SEAMAP surveys, Marancik et al. (2012) documented a shift in species dominance from spring spawning (most of the commercial species) to fall spawning species.

Hydrographic data collected from CTD casts at each SEAMAP station provide "real-time" CTD data immediately available to the global oceanographic community. The CTD data are an important real-time product because they include temperature and salinity at depth, both parameters impossible to determine from satellites but both key parameters to include in ocean modeling. The CTD data are checked at sea and then passed by Internet connection to servers shared with NOAA partners at the Stennis Space Center (National Coastal Data Development Center and National Data Buoy Center), where they are transmitted into the Global Telecommunications System as part of the Global Temperature Salinity Profile Project. The US Navy's Naval Oceanographic Office assimilates the data into daily runs of several large whole basin deep ocean models, as well as the smaller subdomains of the GOM.

Core SEAMAP plankton data from 1982 to present consisting of station information, summarized environmental measurements, sample information, sample displacement volumes, counts of fish eggs, and ichthyoplankton identifications and measurements are available upon request as a distributable data set, but are not available online. Data are delivered with documentation outlining program information, points of contact, survey designs, sampling and identification protocols, data formats, and suggestions for working with the data. Both data and documentation are provided in formats compatible with common commercial and open-source software packages. There is typically a one- to two-year lag in data availability for the most recent surveys due to sample shipment, processing, archiving, quality control, and resourcing levels. Currently, the distributable data set contains only the original identifications and not the corrected or modified data resulting from re-examination of specimens. Digitized cruise reports for the majority of NMFS SEAMAP cruises are available online at http://www.sefsc.noaa.gov/ldscruises/index.jsp and, for more recent state surveys, at http://seamap.gsmfc.org/listcruises.php.

Data processing, cataloging, and archiving for SEAMAP hydrographic profile data have not been centralized. Hydrographic profiles have been taken on NMFS-conducted surveys since the late 1980s but have only been consistently processed, cataloged, and archived since 2000. The majority of the raw and processed data from these surveys is archived offline by individual survey and station. Limited profile data in 1-meter depth bins from state surveys are available in the SEAMAP database maintained by the Gulf State Marine Fisheries Commission (GSMFC) at http://www.sefsc.noaa.gov/ldscruises/index.jsp. Raw and processed profile data from state surveys, if available, will be archived with the individual states. The distributional data set and the Gulf States Marine Fisheries Commission SEAMAP data can be linked with minimal effort.

HOW MIGHT THE SURVEYS BE IMPROVED?

Can New Technologies Increase Ability to Meet Survey Goals?

The short answer is yes. The power of the long-term fisheries oceanography surveys comes from the continuous collection of data using consistent methodologies over decades. These data provide a baseline for assessing future changes in the ecosystems and also provide information as to the current status of the ecosystems. Many of the sampling technologies used are decades old, and this consistency contributes to the value of the programs. However, there is broad recognition of the value of new technologies, and there are many examples of these technologies being evaluated and in some cases used in the survey programs.

Another important function of new technology should be to provide interpolation between seasonal-scale ship-based surveys. Higher-resolution data are necessary to capture episodic events that may not be encountered by quarterly (e.g., CalCOFI) or biennial (e.g., EcoFOCI) surveys, but may have a major effect of the ecosystem. Detecting changes in phenology also generally requires higher temporal resolution sampling. Satellite remote sensing, high-resolution models, gliders, and mooring arrays are key to interpolating the fields sampled by the surveys. Here, we discuss only a few potential uses of new technologies.

Towed or Ship-based Imaging Systems

Many of the survey programs are evaluating the use of imaging systems for enumerating the abundance and distribution of plankton. Systems evaluated include the Video Plankton Recorder (VPR; Davis et al., 1996), the In Situ Ichthyoplankton Imaging System (ISIIS; Cowen and Guigand, 2008), the Shadow Imaging Particle Profiler and Evaluation Recorder (SIPPER; Samson et al., 2001; Remsen et al., 2004), and the Submersible Flow Cytometer (FlowCytobot; Olson and Sosik, 2007). These imaging systems complement net-based sampling, but nets will certainly be needed to collect specimens for genetic, food habit, stable isotope, growth, and condition studies. Whether these optical systems will be able to replace nets for monitoring abundance and distribution remains to be seen and at present there are several challenges to be overcome. First, the systems are designed for long transect runs rather than the current practice of repeated deployment and retrieval of nets. So the optical systems need to be redesigned or the sampling design of the surveys needs to change. Second, the image processing software is not yet sufficiently automated to permit rapid processing of the voluminous data collected, and a significant amount of manual processing is still required. Third, it is dubious whether the detailed species and stage level identification would be possible with optical systems. Many of the products coming from these surveys are based on species-level identifications. Efforts should continue to incorporate these imaging systems into fisheries oceanography surveys, but for many applications, they will only be able to complement rather than replace net-based observations.

Gliders

Gliders also offer a new method for collecting physical, chemical, and biological data. They can be used independently or coupled with current ship-based surveys, depending on the specific goals of the survey. Glider measurements include temperature, salinity, density, fluorescence, and currents (Todd et al., 2011). This suggests that if gliders were integrated into survey operations, the number of CTD profiles could be reduced (i.e., replaced with glider data), and the understanding of currents would be increased. However, such replacement would have implications for water samples taken from the CTD rosette bottles on each cast because gliders do not yet provide many of the measurements taken from bottle samples, such as oxygen, nutrients, primary productivity, chlorophyll, phaeopigments, high-performance liquid chromatography, dissolved inorganic carbon, and total alkalinity. Nevertheless, in the near future, it is likely that oxygen, nitrate, and better-calibrated fluorescence measurements will routinely be obtained from gliders. Coincident biological and physical observations will still be needed to match physics to fish, so that gliders could complement hydrographic measurements made by NMFS but not replace them.

Gliders can also be equipped with echosounders and plankton imaging systems to add more biological observations. Wave gliders operating on CalCOFI lines could collect multifrequency acoustic measurements that might replace shipboard acoustic measurements (see Greene et al., 2014, in this issue). This would require a small fleet of wave gliders, but the benefits would be increased synopticity and potentially much more frequent coverage of the CalCOFI spatial domain than the quarterly surveys provide. The need for ground truthing of acoustics by trawling is still as important for glider acoustics as it is for shipboard acoustics. Gliders can also host plankton imaging systems. For example, the EcoFOCI program in Alaska and the EcoMon program in the Northeast are exploring the use of gliders with mounted camera systems like ISIIS or the VPR as an alternative to net-based sampling. The same challenges identified above exist for imaging systems on gliders, with the additional problems of onboard storage and retrieval of imagery. The application of gliders in these long-term survey programs is largely limited by resources: the cost of the system and the cost of personnel to operate the systems. These costs can be partially overcome by greater cooperation within NOAA and between NOAA and the Regional Integrated Ocean Observing Systems.

> "We hope that this review will help to clarify the value of these surveys to decision makers so that we can continue to collect time series that are fundamental for assessing long-term changes in the oceans around the United States."

New Sensors

The addition of new sensors to ongoing operations is a straightforward way to add value to current surveys. Instruments have been integrated into flow-through systems through cross-NOAA collaborations (pCO_2, pH with the Atlantic Oceanographic and Meteorological Laboratory and Pacific Marine Environmental Laboratory). Sensors have been added to CTD casts, including those for dissolved oxygen and Laser In-Situ Scanning and Transmissometry. Finally, smaller bongo nets have been attached to the wire above the regular bongo frame to allow collection and ethanol preservation of zooplankton and ichthyoplankton for genetic and otolith studies. Redundant collection of samples is increasingly important as genetic, trace element, biochemical, and physiological methods are added to the fishery oceanography tool kit.

The use of devices mounted to moorings also provides year-round information that supplements temporally specific survey data. As an example, Tracor Acoustic Profiling Systems have been used over the past several years to continuously measure zooplankton displacement biovolume and size distribution in the eastern Bering Sea and the Arctic (Jeffrey Napp, NOAA/Alaska Fisheries Science Center, *pers. comm.*, September 15, 2014).

Can Survey Effort Be Reduced and Still Meet Survey Goals?

The simple answer is no, but efficiency can be gained by re-evaluating sampling design relative to survey objectives, the introduction of new survey design tools, and greater cooperation among NMFS elements conducting surveys.

The goals of the long time series fisheries oceanography programs in the United States require sampling over large spatial domains with at least annual frequency. Many programs have multiple objectives that require sampling over large spatial scales. Many surveys encompass the spawning areas of most managed species within a system. Reducing the area of a survey potentially creates a bias if species use of the system is changing through time as a result of climate variability. Additionally, there is scientific rationale in many regions to expand the spatial effort, not decrease it. For example, as it stands now, the Gulf of Mexico is only sampled in US territorial waters. Expansion of surveys into the southern Gulf (i.e., into Mexico's territorial waters) would be, from a management perspective, quite desirable. As another example, much of the discussion about sampling domains in CalCOFI has emphasized the massive reduction in the spatial and temporal coverage from the original monthly sampling off California and Baja California in the 1950s to the current quarterly sampling of six core lines off southern California (Figure 1). Reviews have usually addressed whether the current sampling is adequate and how the core area might be extended. In the Northwest, the RREAS survey expanded its range (and number of days at sea) in response to concerns that the historical core area was insufficient to adequately assess impending year class strength for key coast-wide populations. Many of these changes in sampling area have been carefully evaluated, and new tools (e.g., Ocean System Simulation Experiments; Lin et al., 2010) will allow even more thorough evaluation of the effects of potential survey changes on survey goals and products.

The timing of surveys is also important and tied to the survey objectives and the regional oceanography. In the Northeast, the seasonal cycle (and variability and changes in this cycle) requires sampling year-round. There is a growing realization that changes in the seasonal cycle may affect availability to both fishery-dependent and fishery-independent surveys. Currently, the survey effort has been reduced from six coverages per year to four, with an emphasis on the fall to spring period. Data are now lacking for late spring and summer, periods that include commercially important species such as Atlantic mackerel, bluefish (*Pomatomus saltatrix*), and black sea bass (*Centropristis striata*). This change was forced by budget reductions and the effect on various products has not yet been evaluated.

Ship time is always a consideration when it comes to planning surveys, especially when budgeting constraints arise. Many of these surveys are dedicated, and issues of sea-day allocation, staffing, and sample processing are potentially limiting. However, some of the surveys discussed here are piggybacked on other surveys. Both the Northeast (EcoMon) and Southeast (SEAMAP) piggyback hydrographic and plankton operations on dedicated trawl surveys. In the SEAMAP program, the piggybacked survey design is different than the dedicated cruise survey design. Utilizing two different survey designs decreases the overall efficiency of these piggybacked surveys and reduces the number of stations sampled due to the transit time between trawl and plankton stations. In the EcoMon program, plankton and hydrographic operations are given second priority to trawl survey operations and, as a result, fisheries oceanography stations are "dropped" on many trawl surveys. Although the situation is changing, at present, NOAA still prioritizes single-species assessment and protected species assessment surveys over integrated, interdisciplinary surveys, which is one institutional impediment to the development of ecosystem-based fisheries management.

A potential improvement in survey efficiency may be in the use of spawning habitat models to direct sampling effort during a survey. For example, since 2008, daily satellite imagery has been used to direct additional sampling during the spring SEAMAP survey. The "off-grid" sampling is based on a spawning habitat model for bluefin tuna with the purpose of developing a more precise index for Atlantic bluefin tuna (Muhling et al., 2010). Similarly, a habitat model was developed for butterfish based on coincident hydrographic and trawl survey data collected on piggybacked surveys during the NEFSC trawl survey. The habitat model was used to estimate the amount of total butterfish habitat sampled during each annual survey and thus the availability of butterfish to the survey. A further example is the sardine habitat model (Zwolinski et al., 2011) used to guide sampling in the coastal pelagic survey of CalCOFI lines along the central California coast following the spring CalCOFI survey (Figure 1).

Another potential improvement would be greater integration of fisheries, protected species, and fisheries oceanography surveys. In the Northeast, numerous projects have been coupled with the EcoMon surveys, adding value to both the specific project and the general goals of the survey. However, these represent relatively short-term collaborations. In the Southwest, the spring CalCOFI survey is one component of a larger two-ship effort to sample from San Diego to San Francisco. CalCOFI provides a much broader suite of measurements and extends further offshore, while the concurrent coastal pelagic fish survey focuses on acoustics, trawling, and daily egg production measurements for the Pacific sardine assessment. Using two ships is an effective way to combine the very different sampling requirements of CalCOFI and the coastal pelagic fish survey. Another example of collaboration is the Recruitment Processes Alliance (RPA) between the EcoFOCI program and colleagues from the Ecosystem Monitoring and Assessment, the Resource Ecology and Ecosystem Modeling, the Resource Energetics and Coastal Assessment, and the Marine Acoustics and Conservation Engineering Programs that began in 2012 at AFSC. One objective of the RPA is to work cooperatively to provide mechanistic understanding of factors influencing recruitment of walleye pollock, Pacific cod, and arrowtooth flounder in the Gulf of Alaska and the Bering Sea, effectively streamlining program effort and lending efficiency to survey sampling, processing, and data syntheses. As part of the RPA, field survey time was blended between EcoFOCI and the Ecosystem Monitoring and Assessment Program, which permitted expansion of the spatial extent (nearly double) of the ichthyoplankton and age-0 surveys in the Gulf of Alaska and Bering Sea. In consequence, however, the frequency of the surveys was changed from annual to biennial such that the Gulf of Alaska is now sampled in odd years and the Bering Sea is sampled in even years. This shift was necessary to provide an estimate of climate impacts on fitness of age-0 groundfish that has been linked to the recruitment of age-1 fish (Heintz et al., 2012). Certainly, this modification limits the temporal resolution of factors influencing the high-frequency, interannual variability in recruitment, but the cooperation has resulted in interdisciplinary surveys with common goals that seek to understand the resource in the context of the ecosystem, which is the underlying goal of fisheries oceanography.

CONCLUSIONS

The value of long time series fisheries oceanography surveys for fisheries management, research, ecosystem-based management, and climate and environmental research is clearly demonstrated by the numerous applications described in this review. The demands for fisheries oceanography surveys to serve multiple users are increasingly intense as ship capabilities and costs increase. There is pressure to combine surveys to achieve efficiencies, as well as to make more measurements to maximize the use of complex and expensive vessels. These changing demands have led to many additions to the sampling, and in some cases to protracted negotiations over what is sampled and where. It can be difficult to maintain consistent long time series in the face of such shifting demands. In some cases, the sampling needs of ecosystem-focused and stock assessment-focused surveys preclude their combination because the compromises required would lead either to loss of critical data or to unacceptable changes in the area or the timing of sampling. Simulations and data analyses should be conducted to test the effects of changes in sampling design or reduction in effort. Results of such tests would be informative and useful for quantitatively evaluating possible changes to surveys.

The scope of long time series and their value for science and management inevitably evolves from their original purpose. Many surveys began by addressing specific regional questions or crises, but have acquired much larger value by virtue of the long time series that can be used to analyze questions that are outside the initial focus. The fact that these data can be used to address many different questions and issues is one reason why they have survived and why they should be continued. With each passing year, and the extension of the time series, the value of the surveys increases and the science yield per unit cost of the entire series increases. The number of peer-reviewed publications and reports that have drawn on data from these series is very large. A recent review of the CalCOFI program (McClatchie, 2014) cited 600 peer-reviewed publications just for the fisheries aspects of CalCOFI. If all related publications from the surveys described in this review were assembled, the number might well be on the order of three to five thousand, an impressive scientific yield.

Each of the long time series described in this review has "core sampling areas" that are surveyed consistently, permitting long-term comparisons, evaluation of trends, and estimates of variability. Consistency in core areas is a fundamental difference from other long-term sampling programs. There are other long-term fisheries surveys in the United States, but the surveys described here measure fish populations (in egg, larval, and juvenile stages), the pelagic prey and predator environments, and hydrographic variables and thus represent a fundamental piece of ecosystem-based fisheries management that provides consistency, coherence, and long-term comparability of marine ecosystems.

Declining funding for long time series and the threat of funding cuts in years of budgetary constraint that would create gaps in the time series are major concerns. Koslow and Couture (2013) recently raised these issues, but the issues are not new. By 2004, the University of California was forced by changes in the State of California budget to cut funding support for CalCOFI (for an interesting perspective on how it happened, see "The CalCOFI Funding Crisis of 2003" by Ralf Goericke in McClatchie [2014]). NOAA picked up the funding because CalCOFI was important to NOAA's mandates, and CalCOFI is now fully funded by NMFS. Today, long-term sampling programs are again being cut. In 2013, the NEFSC ended their CPR surveys that began in 1963 and represented the longest plankton time series in the Northwest Atlantic Ocean. Researchers are struggling to find other sources of funding. Cuts to long time series fisheries oceanography programs should be viewed from the perspective of how much these data contribute. We hope that this review will help to clarify the value of these surveys to decision makers so that we can continue to collect time series that are fundamental for assessing long-term changes in the oceans around the United States.

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