*Northeast Consortium Cooperative Research*

# PULSE: A Cooperative Partnership for Coastal Ocean Ecosystem Monitoring in the Gulf of Maine

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**Abstract**

This project demonstrates a successful partnership for a cooperative, industry-based contribution to monitoring of the coastal pelagic ecosystem in the western Gulf of Maine. The need for long-term biological data collection in the Gulf of Maine is critical in light of the potential for climate change and accompanying ecosystem change at both the regional and global scale. It is increasingly important for the fishing industry as decisions about fishery management shift from a single or multi-species to an ecosystem-based approach. In this final report, we describe the major results of a two year time series of hydrographic and zooplankton and ichthyoplankton data carried out between January, 2007- December, 2008 at five fixed stations in the western Gulf of Maine. We place these results in the context of an overview of the entire five year time (2003-2008, excluding 2006) series collected as part of the PULSE project supported in previous years by the Northeast Consortium. The sampling for the 2007-08 time series was undertaken totally by the fishing industry, and analysis of samples was conducted at the University of Maine, Gulf of Maine Research Institute laboratory. This is the first recorded time series for the western Gulf of Maine showing both seasonal and interannual variability zooplankton and ichthoplankton abundance and biodiversity. Major findings include evidence for a marked reduction of abundance of *Calanus finmarchicus*, a dominant Gulf of Maine planktonic copepod that is a primary prey for adult herring and the northern right whales, in 2004-2005, particularly in summer on Jeffreys Ledge, and seasonal and interannual variability in both ichthyoplankton and zooplankton species diversity. In addition to providing indicators of plankton abundance, the time series results serve fundamental data needs for coupled physical biological models investigating coupling between climate forcing, physical circulation and mixing, plankton production and recruitment processes in the western Gulf of Maine. Recommendations for future research and steps to continue the partnership and maintain an industry-based contribution to the regional observing system are proposed.

## Introduction

The overall goal of this project was to design and develop a cooperative, industry-based contribution to monitoring of the pelagic ecosystem in the Gulf of Maine. The need for long-term biological data collection in the Gulf of Maine is critical in light of the potential for change in climate at both the regional and global scale. It is increasingly important for the fishing industry as decisions about fishery management shift from a single or multi-species to an ecosystem-based approach. The project has involved the expertise and resources of the local fishing community in the process of learning more about the natural and man-made variability of the Gulf of Maine marine ecosystem.

In this final report we demonstrate that a cooperative, industry-based contribution to monitoring is logistically feasible. We present highlights from time series of observing data on interannual and seasonal variability and zooplankton and ichthyoplankton abundance and diversity at fixed stations sampled in the western Gulf of Maine. The fishing industry provided vessels and participated in collection of samples at weekly to semi-monthly intervals. The sampling involved relatively inexpensive, "low-tech" techniques and equipment that can be readily learned and routinely deployed on fishing vessels. The sample analysis was carried out in the laboratories at the University of New Hampshire and the University of Maine at the Gulf of Maine Research Institute.

*Why monitor the pelagic ecosystem in the Gulf of Maine?*

The earth system, which includes the atmosphere and the oceans and all life that inhabits them, is a dynamic balance that is subject to change. Over the past 50 years, the world's oceans have been warming (Levitus et al. 2000), in a trend well correlated with the observed increase in average temperature in the lower atmosphere (Albritton, Meira Fiho et al. 2001). Paleoclimatologists have recently discovered that when the earth system is being forced, as in the emergence from the last ice age, large, abrupt climate shifts have occurred, locally reaching as much as a 10 °C change in 10 years (Cuffey and Clow 1997; Alley 2000). The implication for the present, when climate is being forced by increasing greenhouse gases, has motivated a group of earth system scientists to announce the possibility of abrupt climate change in the foreseeable future (Alley et al. 2002).

Superimposed on the recent trend in warming over the past century are fluctuations of atmospheric and ocean processes (including fishing) at smaller scales that in some instances have led to a rapid transition to a different oceanographic ecological states ("regime shifts" or "tipping points"). These shifts are associated with major changes in abundance and composition of fish stocks (e.g. Steele 1998). Examples include the oscillations of anchovy and sardine populations in the California Current ecosystem, the collapse of North Sea herring populations in the Middle Ages, fluctuations in herring, salmon and halibut catches off British Columbia associated with climate shifts in the North Pacific, the shift from gadoids to pelagics in the North Sea in the 1960's and 70's and the collapse of the northern cod off the Canadian coast in the early 1990's, which was accompanied by an increase in shrimp and crab (see references in Mann 2000; Dower et al. 2000; Frank et al. 2005).

In many of these cases, there is evidence that ecological regime shifts are driven by changes in the dynamics of phytoplankton and zooplankton at the base of the pelagic food web (e.g. Mann 2000; Pershing et al. 2005; Greene and Pershing 2007) occurring faster than a fish stock's capability to adapt to them. A characteristic of many of the recorded collapses in fish stocks is that heavy fishing pressure continued after a series of recruitment failures caused by adverse environmental conditions (Larkin 1996; Cushing 1996).

In their report to the National Academy of Sciences, the international committee on Abrupt Climate Change points out that human and natural systems have survived abrupt changes in the past; the best way for effective response is for increased knowledge to reduce the vulnerability to consequences and increase the capacity to adapt. They argue for better monitoring activities, including tracking of oceanic regimes of intense biological activity, particularly near the coasts. Similarly, many in the fisheries oceanography research community argue for increased monitoring of oceanic ecosystems as a necessary step for fisheries management strategies in the context of the potential for change (e.g. Sharp 2000; Dower et al. 2000).

The potential for climate change is predicted to affect the pattern of New England's weather (New England Regional Assessment Group 2001). The average air temperature is predicted to increase by 3-5°C and snow fall and precipitation levels may change, with implications for patterns of river runoff into the Gulf of Maine. An increasing trend in surface temperature in winter along the northeastern U. S. coast, including the Gulf of Maine, at a rate of about 2°C per 100 years, has recently been documented (Shearman et al. 2004). At the same time, change is occurring in the level of human activity along the Gulf of Maine coast. The southern coast of Maine, in particular, is predicted to become increasingly urbanized over the next few decades.

What effects, if any, these potential regional changes would have on circulation and water temperature in the Gulf of Maine and on the productivity of its ecosystems and fisheries, is not at present predictable, although recent developments in coupled physical-biological modelling of the Gulf of Maine- Georges Bank system (e.g. Miller et al. 1998; Ji et al. 2008) promise new levels of understanding of connections between ocean circulation and temperature and plankton productivity and distribution. Common sense dictates that it would be advantageous to know whether change is occurring in the Gulf of Maine oceanic ecosystem, with its potential consequences for the recruitment and distribution of fish stocks, in order to better prepare for it. The Gulf of Maine now has a Closed Area, in the vicinity of Jeffrey's Ledge, the main purpose of which is to protect the habitat and spawning stocks of Gulf of Maine groundfish. Knowledge of change in the structure and productivity of planktonic communities will contribute to accurate assessment of the effectiveness of the Closed Area , and of any future Marine Protected Area that may be designated in the Gulf of Maine (Anon. 2001).

*The Canadian Atlantic Zonal Monitoring Program (AZMP)*

Shortly after the collapse of the northern cod stocks in the early 1990's, the Fisheries Research Conservation Council, composed of government and university scientists and members of the fishing sector, recommended that the Department of Fisheries and Oceans increase the monitoring capacity for the biological environment in waters of Atlantic Canada. The Department responded with a proposal for a Zonal Monitoring Program (Therriault et al. 1998) to meet the needs of the FRCC for more information about variability, trends and the possibilities for regime shifts in Atlantic waters supporting the fisheries. The biological observation program comprises a number of components, including section sampling for plankton during existing fish surveys, remote sensing, Continuous Plankton Recorder measurements, and toxic algae monitoring. Most of these components were already in place. A new and cornerstone activity of the AZMP is the establishment of six fixed stations located in the Bay of Fundy, Scotian Shelf and Gulf of St. Lawrence. The fixed stations are intended to complement the coarser temporal resolution of other monitoring components with higher-frequency data on seasonal patterns of phytoplankton and zooplankton at accessible yet strategic locations across the zone. After over a year of inter-regional meetings and discussions a list of key biological variables and protocols were defined and sampling commenced in 1999. A description and summary of the results of the program are provided by Pepin et al. (2005; see also http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/index-eng.html).

*Present zooplankton/ichthyoplankton observing activities in the Gulf of Maine*

A number of monitoring and observing programs are currently, or have been until recently, conducted in the Gulf of Maine (Chandler 2001). While these programs address numerous aspects of the Gulf of Maine system, very few sample the planktonic ecosystem in the water column away from the nearshore environment. GoMOOS (Gulf of Maine Ocean Observing System: http://www.gomoos.org) has focused on providing real or near real time information on ocean temperature, currents, waves, wind and other oceanographic parameters using moorings and seaward looking shore-based high-frequency radar. Several of the buoys, including buoy "B" now measure chlorophyll at 3 and 18 m as well as light levels. The Northeast Fisheries Science Center (National Marine Fisheries Service) samples zooplankton on the ECOMON surveys (formerly MARMAP: Marine Resources Monitoring, Assessment and Prediction; Sherman et al. 2002) program, which includes four to six surveys a year since 1977, presently at about 30 stations sited randomly across the Gulf of Maine. NMFS also supports a Continuous Plankton Recorder transect that measures relative abundance of zooplankton at the surface in the deep, central Gulf of Maine at monthly intervals (e.g. Pershing et al. 2005). Between 2002-2008, the Coastal Ocean Observing Center (COOA: Center of Excellence in Coastal Ocean Observation and Analysis) conducted sampling at monthly intervals along two transects, one extending from Portsmouth Harbor to Wilkinson Basin and the other from Portsmouth along the coast to the Kennebec Estuary. The measurements include hydrography, optical properties of seawater, chlorophyll and microplankton composition and zooplankton abundance.

Observing activities in the Gulf of Maine are presently overseen by NERACOOS (Northeast Regional Association of Coastal Ocean Observing Systems: www.neracoos.org), whose mission is to lead the development, implementation, operation, and evaluation of a sustained, regional coastal ocean observing system for the northeast United States and Canadian Maritime provinces, as part of the United States Integrated Ocean Observing System (IOOS). NERACOOS was established as a non-profit organization in November, 2008. Its activities are currently focused in four areas: coastal ecosystem health, coastal hazards resiliency, ocean energy and maritime safety and security. The coastal ecosystem health focus aims to protect a range of coastal ecosystems by building regional partnerships to achieve economies of scale and applying principles of ecosystem based management. However, current shipboard activities within NERACOOS do not presently observe change in coastal Gulf of Maine zooplankton and ichthyoplankton communities.

*PULSE: A contribution to the regional observing system by the local fishing communities*

We have named our Northeast Consortium cooperative project *PULSE* to connote the ability to track the health of the Gulf of Maine pelagic ecosystem by tracking plankton populations. Similar to the Canadian AZMP program, this tracking is done at fixed stations at a relatively high frequency (weekly to semi monthly intervals). This sampling frequency is not achieved by other Gulf of Maine sampling programs, especially for zooplankton. PULSE therefore has provided a necessary complement to the existing Gulf of Maine monitoring activities. It has provided observations of seasonal and interannual change in zooplankton and ichthyoplankton communities that are needed to document the timing of biological events and to test coupled physical-biological model predictions of climate forcing on coastal pelagic ecosystems. A longer time series is even more valuable, as it would provide insight not only of the seasonal timing of biological events in the inshore pelagic ecosystem but also into the extent of interannual variability and longer term trends in species biodiversity, plankton productivity and ecosystem structure. These observations meet the need of NERACOOS for assessment of climate change impacts on the coastal pelagic ecosystem (e.g. RARGOM, 2005), which the NOAA ECOMON and CPR surveys that sample further offshore do not provide.

**Project objectives**

The overarching project objectives were to (A) provide a framework for a cooperative partnership between the fishing and scientific research communities for collection of time series data showing seasonal, interannual and longer-term variation in plankton and hydrography, (B) demonstrate its feasibility by sampling at coastal fixed stations in the western Gulf of Maine and (C) acquire and interpret a multiyear time series of zooplankton and ichthyoplankton data. Specific objectives for the 2007-2008 award were established as follows:

1. Expand an effective and sustainable cooperative partnership for monitoring of key hydrographic, zooplankton and ichthyoplankton variables at 5 stations in Ipswich and Massachusetts Bay.
2. Create regional capacity within the commercial fishing fleet to undertake current and future cooperative research. Equip and train commercial fishermen to work independently to undertake the proposed sample collection protocols.
3. Provide high quality data products documenting time series of zooplankton and ichthyoplankton for end users. A critical part of the data collection is the record of

abundance of *Calanus finmarchicus* at the Jeffreys Ledge station as well as at other stations representing the Ipswich and Massachusetts Bays.

4. Participate in workshops and information exchange sessions with fishermen and end users. These time series and the physical biological models that will use the data represent new information and approaches to ecosystem based management that need to be presented, discussed and evaluated by the regional fishing and management communities.
5. Consult with fishermen to groundtruth findings based on their empirical knowledge of seasonal fish distribution and abundance in the western Gulf.
6. Coordinate results from this project with other MFP, university and government research projects studying juvenile habitat and nursery areas.
7. Use the data and time series in physical biological model studies and in combination with other research surveys in Ipswich and Massachusetts Bays to develop and test hypotheses about interactions between circulation, plankton production cycles and feeding and reproduction of fish in the western Gulf of Maine.

**Project participants**

***Project Principal Investigators***: Jeffrey Runge (UNH) and Rebecca J. Jones (UNH)

***Monitoring Advisory Panel (2002-2004)*:** R. Barnaby (UNH), C. Goudey (MIT Sea Grant), S. Meeker (UNH Sea Grant Extension), L. Mercer (Maine DMR), D. Mountain (NMFS, Woods Hole), C. Pendleton (NAMA), D. Townsend (U Maine)

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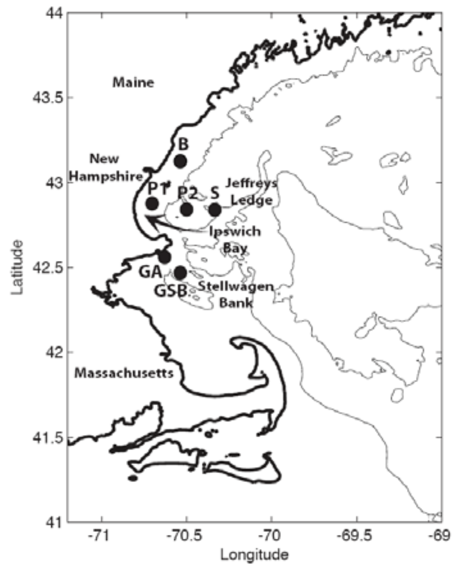
**Methods**

The underlying conceptual approach to this project is that sampling at fixed stations at intervals less than the normal generation time (i.e., sampling frequency > 1 month$^{-1}$) of zooplankton provides indicators of seasonal and interannual change in fundamental ecosystem properties related to zooplankton abundance, diversity and productivity. The fixed stations themselves are presumed to be representative of large areas of the coastal, advectively coupled western Gulf of Maine. The sampling protocols were chosen to rely on robust or low technology equipment that could be operated under variable sea conditions without need for specialized technical training. To standardize comparison among years and across regions, the same protocols used in the Canadian Atlantic Zonal Monitoring Program were adopted here.

*Study Area*

Sampling was conducted at two stations in Massachusetts Bay (MB) and three stations in Ipswich Bay (IB) off the coast of southern New Hampshire. The MB stations were located just south of Gloucester, MA, with the closest one adjacent to GoMOOS Buoy “A” (referred to hereafter as GA) and the furthest station located at the northern tip of Stellwagen Bank (GSB). The three IB stations were located along a transect starting with a nearshore stations south of the Isles of Shoals (referred to hereafter as P1), a station in Scantum Basin (P2) and a station located on New Scantum (S) of Jeffreys Ledge. This latter station “S” had been sampled since the beginning of the PULSE project in 2003. The depth of Gloucester station “GA” was 65m and “GSB” was 82m. Station P1, P2 and “S” station depths were 70m, 125m and 40m respectively.

Fig. 1. Station locations for the 2007-2008 PULSE time series (isobath: 100m). Stations in Ipswich Bay (P1, P2) and on Jeffreys Ledge (S) sampled by NH fishermen. Stations in Massachusetts Bay (GA and GS sampled by fisherman in the Mass. Fishermen's Partnership.




*Sampling Protocol*

Sampling was conducted semi-monthly aboard commercial fishing vessels equipped with a winch and gantry capable of towing bongo and ring zooplankton nets. Fishermen involved in this collaborative program were trained by R. Jones in the deployment of the equipment and handling of the samples, after which they carried out the sampling routine on their own. Regular communication and site visits ensured that equipment was functioning properly and that protocols were being followed.

Ichthyoplankton samples were taken with a standard, 0.65m diameter MARMAP bongo net (Sea-Gear Inc.) fitted with 500 µm mesh nitex plankton nets on both sides. Volume of water filtered was estimated by suspending a General Oceanics flowmeter in the mouth of each net. Bongo tows were standardized by limiting the tow duration to a total of 10 minutes, with the upcast and downcast divided evenly. Nominal maximum tow depth was within 5 meters off the bottom. Tow speed of the bongo did not exceed 2 knots and a 45 degree angle in the tow cable was maintained.

Ichthyoplankton were sorted from the preserved samples with the use of a light table and transparent tray. All larvae and eggs were preserved in smaller vials for archiving. Taxonomic identification and length measurements were taken at a later time. The remainder of the total sample was split in half with a Folsom plankton splitter and half was saved for future zooplankton analysis and the remainder was discarded. All larvae were identified to the species level when possible.

Digital images of the individual larvae were taken with a Leica DFC290 digital camera mounted on a Leica MZ20 stereoscope. Standard length (snout to tip of notochord) of larvae and egg diameter were measured with ImageJ software. Either all or a maximum of 100 random larvae, whichever was smaller, were measured per species. An image of a stage micrometer was taken at every measuring session and at every magnification used during that session to calibrate the software.

Zooplankton samples were collected with a 0.75 m diameter, 200-µm mesh ring net in the mouth of which a General Oceanics flowmeter was suspended. Duplicate ring net casts were deployed vertically to within 5 meters off the bottom and retrieved at a rate of 40 m/min. All samples were preserved in 4% buffered formaldehyde and seawater. All zooplankton samples were split in half using a Folsom Plankton Splitter. Half of the sample was archived for identification and enumeration of meso-zooplankton species and the other half was used to estimate dry weight biomass.

To estimate zooplankton diversity and abundance, the split archived sample was diluted and a 5-10 ml subsample taken to obtain a target number of 200 organisms. All copepods were identified to species and staged, all other plankton were identified to family or to species where possible. To minimize variability, an additional subsample of 75-200 individuals was analyzed to enumerate stages of *Calanus finmarchicus*, the typically dominant copepod. The counts were normalized to number $m^{-3}$ or number $m^{-2}$, taking into account the subsample dilution factor and split factors and volume sampled by the net from the flow meter reading.

The remaining half of sample was analyzed for dry weight biomass. The sample was removed of preservative by sieving through a nitex mesh screen with mesh size less than or equal to the mesh size of the collection net. Samples were rinsed with 100 ml of freshwater to remove salts and then the screen and sieved sample were placed in a clean, pre-weighed petri dish. Mesh filters and dishes were pre-weighed for subtraction from sample material weight after drying. The samples were dried in a Precision Econotherm Lab Oven at 65 degC for 48 hours. Dried samples were then weighed to the nearest 0.001 gram on PG403-S Delta Range Mettler Toledo precision scale. Final weight $m^{-2}$ was calculated taking into account the split factor and volume filtered by the plankton net.

A SeaBird 19*Plus* with a WetLabs fluorometer was deployed at every station. Each port, Gloucester and Portsmouth, had their own CTD for convenience of sampling. Data was downloaded independently in Gloucester by the Massachusetts Fishermen's Cooperative and emailed to GMRI for analysis. Data from the Portsmouth CTD was downloaded by R. Jones and analyzed at GMRI. All CTD data was processed with the SeaBird Data Processing software and then binned to 1 meter increments.

*Work completed during the performance period*

The sampling was completed as planned (Table 1). Station visits were not always spaced evenly every two weeks, due to weather and equipment limitations. Nevertheless, the samples represent two complete annual cycles at each study area.

Table 1. Number of visits to stations each year in each area.

| Year | Ipswich Bay (NH) | Massachusetts Bay (MA) |
|---|---|---|
| 2007 | 23 | 24 |
| 2008 | 24 | 27 |

Analysis of samples collected in 2008 was completed at the end of June, 2009.

**Data**

The data include files and figures showing measurements of temperature and salinity at all stations, chlorophyll a concentrations (at 6 depths: Stations "B" and "S", 2003-2005), zooplankton biomass, abundance and composition at each station and ichthyoplankton abundance and diversity at stations P1, GA and GS.

The data are served on the PULSE website (www.pulse.unh.edu) which is linked to the Northeast Consortium Database and the BCO-DMO Database located at the Woods Hole Oceanographic Institution. Entry of all data into the database is still in progress, under the supervision of R. Jones.

Presentation of the scientific results of the entire time series collection is in presently in preparation for publication as a series of peer-reviewed research articles. Only highlights of the results are presented in this report.

**Results and conclusions**

In 2007-2008, we expanded the monitoring activities to sample at five stations in the western Gulf of Maine, involving fishermen from both New Hampshire and Massachusetts. Combined with the results from previous years, we have demonstrated an effective and sustainable cooperative partnership for monitoring key hydrographic, zooplankton and ichthyoplankton variables in coastal waters (Objective 1). Member of the commercial fishing fleet were trained to independently conduct the sample collection and the potential for a long term cooperative research partnership was established with the Massachusetts Fishermen's Partnership (Objective 2). Data products documenting time series of zooplankton and ichthyoplankton have been or are in the process of being archived at Northeast Consortium and BCO-DMO data repositories, as discussed above (Objective 3).

As discussed in the presentations section below, we have participated in workshops and information exchange sessions with fishermen and end users. Through participation in NERACOOS, development of new research proposals and other research activities related to needs for observing data in the Gulf of Maine, we hope to show how these time series and the physical-biological models that will use the data represent new information and approaches to ecosystem management (Objective 4). In collaboration with the Northwest Atlantic Marine Alliance (NAMA) Considerable effort was made to consult with fishermen in order to groundtruth findings based on their empirical knowledge of seasonal fish distribution and abundance in the western Gulf (Objective 5).

Now that we have the completed time series data and are in the process of interpreting the overall results, we hope to find opportunities to present the results in workshop settings involving the fishing and management communities. As discussed in sections below, we are coordinating results from this project with other university and government research projects studying juvenile habitat and nursery areas (Objective 6), in particular for Atlantic cod.

The time series data acquired in this project have provided new knowledge of seasonal and interannual change in zooplankton and ichthyoplankton in the western Gulf of Maine. These data serve as the foundation for development of new hypotheses about interactions between circulation, plankton production cycles and feeding and reproduction of fish in this region.

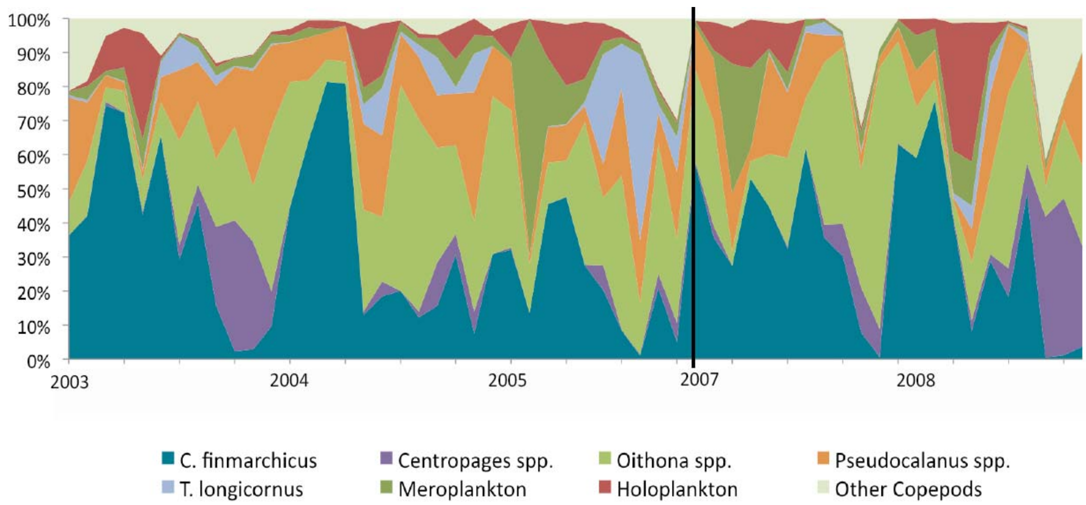



**Figure 2**. Zooplankton species composition collected with a 200µm mesh ring net at a time series station on Jeffreys Ledge, 1003-2007 (no data for 2006). The three most dominant species groups are *Calanus finmarchicus* (blue green), *Oithona similis* (light olive), and *Pseudocalanus* species (orange).

The two years of sampling add to the 3 year time series collected by the previous PULSE project supported by the Northeast Consortium in 2003-2005. The results to date show seasonal and interannual variation in zooplankton species diversity, for example the time series for the Jeffreys Ledge station (Station "S": Figure 2). The zooplankton are dominated by a relative small number of species of planktonic copepods, of which *Calanus finmarchicus* is seasonally prominent in spring and early summer, then diminished in fall and winter to be succeeded by smaller copepod species such as *Pseudocalanus* spp. and *Centropages typicus.* A small cyclopoid copepod, *Oithona atlantica*, has recently become more prominent on Jeffreys Ledge throughout the year. These seasonal and interannual changes are hypothesized to impact the feeding, growth and distribution of pelagic fish, such as herring and sandlance, that feed on zooplankton on Jeffreys Ledge, with subsequent impacts manifested higher up the food web.

For example, the data show interannual variability in abundance of *Calanus finmarchicus* among years on Jeffreys Ledge (Fig. 3). *Calanus* abundance was highest in spring and summer of 2003 and lowest in 2005. The highest CV abundances in late summer, 2003, represent concentrations of 1-10 *Calanus* per liter, depending upon whether they are uniformly distributed throughout the water column (60 m) or in a layer 10 m thick. These concentrations are sufficient to attract foraging herring schools and northern right whales, which feed primarily on *Calanus*. Notable is the decrease in magnitude and extent of the window of availability of the lipid and energy-rich stage CV, the preferred prey for northern right whales, herring and other planktivores, in summer and early fall.

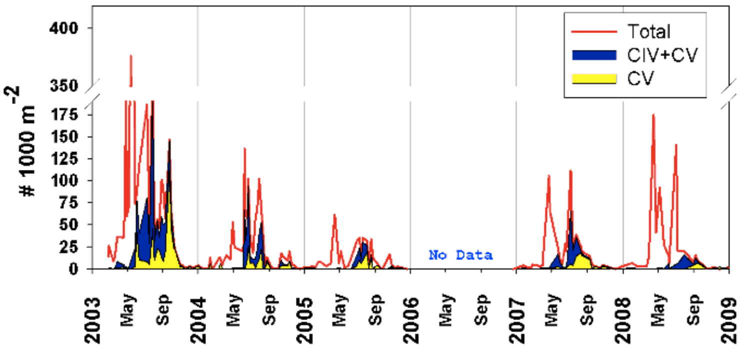



**Figure 3**. Interannual variation in abundance of the planktonic copepod, *Calanus finmarchicus*, at the Jeffreys Ledge station (x-axis is year: 2003-2008; no data in 2006). Red line: total abundance, including nauplius stages. Blue: abundance of Stage CIV and CV. Yellow: abundance of stage CV only, showing interannual variation in window of availability of energy rich forage on Jeffreys Ledge.

We hypothesize that aggregations of adult herring that occur in late summer at the base of Jeffreys Ledge and just south of Jeffreys Basin represent the response of herring to large concentrations of lipid-rich, late stage *Calanus* that concentrate at the head of Jeffreys Basin and overflow onto the ledges. We are presently investigating whether the low, late summer *C. finmarchicus* abundances at the Jeffreys Ledge station are the consequence of high predation by herring on the species in this region or represent much lower production of the species recently in the western Gulf of Maine. The lower production of *Calanus* may be related to warmer temperatures in deep waters of the Gulf of Maine in fall, which is hypothesized to disrupt the diapause component of the life cycle of this species. We anticipate that new coupled *Calanus*-circulation modeling will provide insight into the underlying controls on population dynamics of *Calanus* and distribution of feeding aggregations of herring in this region.

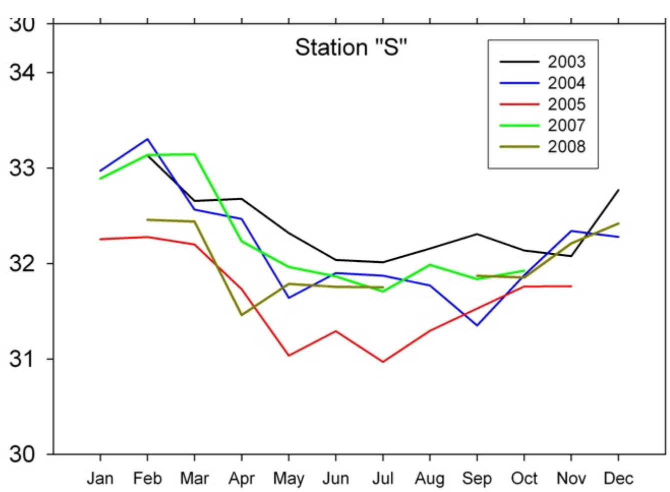



Fig. 4. Average monthly salinity integrated over the water column at the Jeffreys Ledge Station "S", from CTD data collected 2-3 times monthly at the station.

A possible physical correlate to the lower abundances of Calanus is 2005 is the observation of generally lower water column salinity in that year (Fig. 4). The cause of this salinity variation is the subject of active research, and may be related to the high river discharge, early summer storm activity in 2004-2005 or transport of fresher water from the upstream Nova Scotia current (Durbin et al. 2003). In addition, CTD profiles of temperature, salinity and density show characteristic deep mixing in winter and stratification in spring at the two stations. Contours of temperature and salinity over the 5 years of data show timing of stratification and subsequent warming of surface waters in May-June, with both spring warming and fall cooling occurring substantially earlier in 2003 than in 2005.

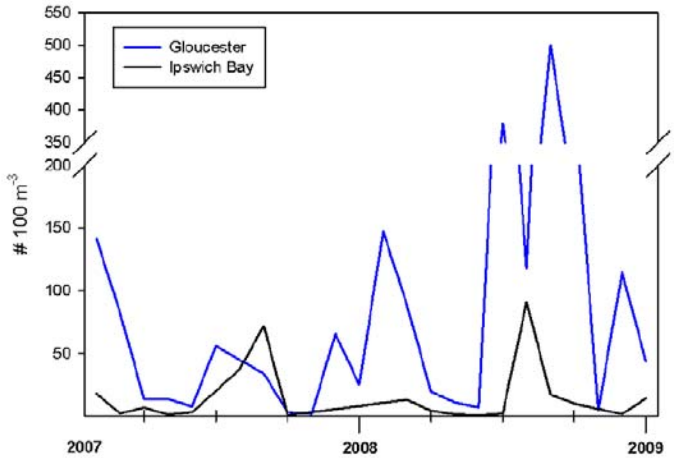



**Figure 5.** Seasonal and interannual variation in total abundance of fish larvae captured in Ipswich Bay and Massachusetts Bay from semi-monthly bongo samples.

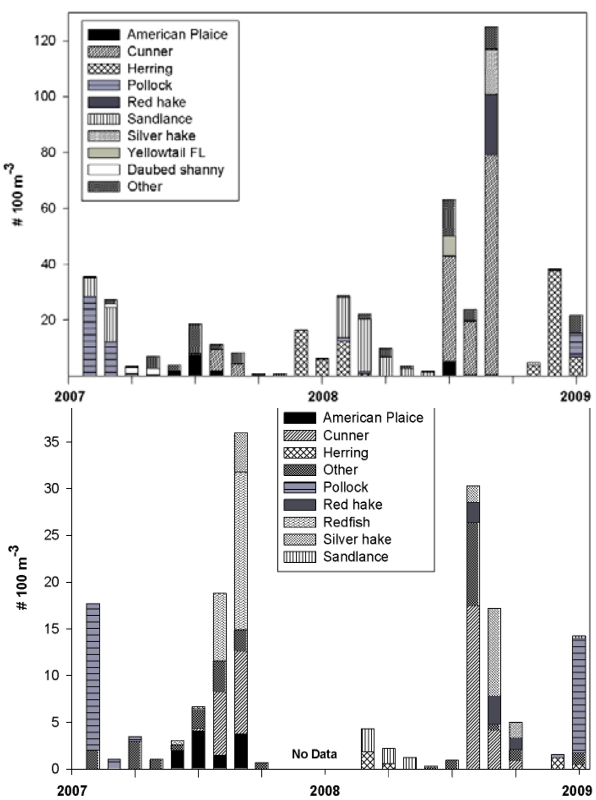



Figure 6. Two-year (2007-08) seasonal and interannual variation in diversity of fish larvae captured in Massachusetts Bay (top panel; mean of two stations) and lower panel (Ipswich Bay;P1). A total of 33 species were observed (N= 5427).

These findings indicate that physical forcing due to climate change will have significant influence on factors determining productivity of the fisheries in the western Gulf of Maine. The impacts may be due not only to substantial variability in the distribution and abundance of lipid rich prey for herring and right whales, but also in determining of recruitment success of herring and groundfish through effects on plankton production cycles and transport of larvae to nursery areas.

The results from the bongo net tows taken at each station and sampling date reveal seasonal and interannual variability in abundance and diversity of the larval stages of the local western Gulf of Maine fish community (e.g., Figures 5 and 6). Herring, pollock and sandlance were most abundant in winter months. Cunner, silver and red hake, American plaice and redfish were most abundant in summer. Together, these 7 species constituted 76% of the total number captured. The data will provide a record of ichthyoplankton that can be used to understand change in the western Gulf of Maine fish community over time.

**Partnerships**

This is a successful project that received enthusiastic and responsible participation from the fishing industry. All fishermen involved have been very helpful and receptive to the idea of this cooperative monitoring project being available for the long-term. The project has been well supported by the industry as a means of supplemental income during the seasons of large area closures and has been well supported during the fishing season as well. Many improvements have been made to make the data collection procedures efficient, data analysis of good consistent quality and data widely available

**Impacts and applications**

The scientific results and demonstrated success of this approach for acquiring high frequency time series data on zooplankton populations argue for development of cooperative partnerships and inclusion of fixed stations in the observing system for the Gulf of Maine. The potential benefit to fisheries and coastal management is informed decision making based on understanding of changes to biodiversity and abundance of key trophic forage species determining distribution of and recruitment into fish stocks in the coastal western Gulf of Maine. The benefit is not immediately, but is a mitigation of the risk of uniformed consequences medium to long term impacts of climate change on the Gulf of Maine ecosystem and its resources.

**Related projects**

- The early phase of the present award was leveraged by grants from the NOAA Coastal Services Center (to the UNH Coastal Observing Center), which contributed to support analysis time of Rebecca Jones.
- Time series results were used to leverage funding of three research grants from the National Science Foundation:
    - C. Davis, R. Beardsley, R. Ji, E. Durbin, J. Runge, C. Flagg and J. Lerczak. *U.S. GLOBEC NWA Georges Bank*: *Processes controlling abundance of dominant copepod species on Georges Bank: Local dynamics and large-scale forcing*. NSF OCE 0733907; Awarded 2005
    - J. Runge and A. Leising. *U.S. GLOBEC NWA Georges Bank: Effects of climate variability on Calanus dormancy patterns and population dynamics in the Northwest Atlantic.* NSF OCE-0733910; Awarded 2005.
    - J. Runge, A. Pershing, J. Pierson, D. Kimmel. *U.S. GLOBEC Pan Regional Synthesis: Life histories of species in the genus Calanus in the North Atlantic and North Pacific Oceans and responses to climate forcing. Awarded 2008.*
- J. Runge was in a position to represent the partnership and its contribution at several meetings of agencies and programs involved in Gulf of Maine monitoring efforts. He is the UMaine representative and former chairman of RARGOM, the Regional Association for Research on the Gulf of Maine. He participated as one of the RARGOM representatives on the Advisory Board for the Gulf of Maine Regional Association. He serves as chair of the Gulf of Maine Census of Marine Life Working Group on Plankton and Pelagic Nekton. He is currently on the Executive Committee of the U.S. GLOBEC Northwest Atlantic/Georges Bank

program and was a member of a Gulf of Maine Zooplankton Working Group sponsored by GoMOOS. He is a member of the Ocean and Coastal Ecosystem Health Working Group within NERACOOS.

- Through the Coastal Observing Center at the University of New Hampshire in collaboration with the Northwest Atlantic Marine Alliance (NAMA), J. Runge and H. Deese organized information exchange sessions with local area fishermen. The goal was to facilitate knowledge exchange between the scientific research and fishing communities in order to (1) develop new conceptual understanding of the application of coastal observation and analysis tools in fisheries management and (2) work toward mutual understanding in the two communities of ecosystem concepts that should be part of ecosystem-based approaches. The NAMA-UNH Coastal Ocean Observing Center partnership succeeded in bringing together small groups of local fishermen and scientists in focused exchanges. In addition to the three meetings that were planned in the original proposal, the project participants also organized a special session at the Maine Fishermen's Forum, an event that attracted approximately seventy participants from fishing-related businesses and occupations, government agencies, universities and public and non-profit organizations. This provided exposure of the project's themes to a broad spectrum of the region's fisheries community. The project was supported in part by an outreach award from the UNH Office of the Vice President.

**Presentations**

The findings and implications of this research have been presented at 16 international, national and local meetings, workshops or seminars in the period 2007-2009, as follows:

- Jones, R.J. and J.A. Runge. 2009. Results of a collaborative monitoring program of coastal zooplankton and ichthyoplankton in the Western Gulf of Maine, 2003-2008. Gulf of Maine Science Symposium. Oct., 2009. St. Andrew’s, NB. Canada.
- Runge, J.A., A. Kovach, R. Jones, S. Tallack, J. Churchill, C. Chen, G. Sherwood, H. Howell, J. Grabowski and D. Berlinsky. 2009. Understanding climate impacts on the spatial dynamics of Atlantic cod in coastal waters of the Gulf of Maine. GLOBEC Open Sciences Meeting. June, 2009. Victoria BC, Canada.
- Runge, Jeffrey, Leising, Andrew, Catherine Johnson and Frederic Maps. 2009. Population responses to environmentally forced shifts in timing of diapause in Calanus finmarchicus in the Gulf of Maine. GLOBEC Open Sciences Meeting. June, 2009. Victoria BC, Canada.
- Runge, J., Leising, A,, Pierson, J., Kimmel, D., Pershing, A., Maps, F., C Johnson, and R. Jones. 2009. Life histories of Calanus species in the North Atlantic and North Pacific Ocean and responses to climate forcing. ICES Working Group on Zooplankton Ecology. March, 2009. Torshavn, Faroe Islands.
- Runge, J. A. and R.J. Jones. 2009. Forage conditions for juvenile Atlantic salmon in coastal waters of the Gulf of Maine. SeaGrant Workshop: Investigation of Nearshore Migration of Atlantic Salmon in the Gulf of Maine Region. Jan. 2009. Portland, ME.

- Runge, J.A., A. Curtis, E. Head, C. Johnson, R. Jones, C. Manning and P.Pepin. 2008. Comparison of zooplankton community structure across seasons and latitudes along the NW Atlantic Continental Shelf. ASLO Summer Meeting. June, 2008. St. John's, Nfld., Canada.
- Runge, J. A. and R. Jones. 2008. Diapause and the recent decline of Calanus finmarchicus in coastal waters of the Gulf of Maine: Implications for the lipid budget in the western Gulf. Feb. 2008. Gulf of Maine Research Institute, Portland, Me.
- Runge, J. A., R. J. Jones and C. Manning. 2008 PULSE: A cooperative partnership for Coastal Ocean Ecosystem Monitoring in the Gulf of Maine. Gulf of Maine Zooplankton Workshop. Feb., 2008. Bedford Institute of Oceanography. Dartmouth, NS. Canada.
- Runge, J. A. and R.J. Jones. 2008. PULSE: A cooperative partnership for Coastal Ocean Ecosystem Monitoring in the Gulf of Maine. GoMOOS session on Gulf of Maine Observing Systems. Maine Fisherman's Forum. Mar., 2008. Rockport, Maine.
- Runge, J. A. , R.J. Jones and C. Manning. 2008. Population dynamics of Calanus finmarchicus in relation to trophic transfer in the western Gulf of Maine: The role of storage lipids. ASLO Ocean Sciences Meeting. Feb., 2008. Orlando, Florida.
- Jones, R.J. and J. A. Runge. 2008. Cooperative, long term ecosystem monitoring in the Gulf of Maine: Observations of mesozooplankton and ichthyoplankton for the period 2003-2007. ASLO Ocean Sciences Meeting. Feb., 2008. Orlando, Florida.
- Runge, J. and C. Johnson. 2008. Needs from models: approaches to the biological questions. ICES Working Groups on Zooplankton Ecology and Physical biological interactions. April, 2008. Sète, France.
- Runge, J. 2008. Linking the coastal ocean ecosystem to fisheries in the northwest Atlantic: the role of models. Biological Oceanography course invited lecture. University of New Hampshire. April, 2008.
- Runge, J. and R. Jones. 2008. Fixed station sampling in the western Gulf of Maine: The UNH COOA and Northeast Consortium PULSE program. RARGOM Theme Session on the Role of Shipboard Sampling in Observing Systems. University of New Hampshire. May, 2008.
- Jones, R. J. and J. A. Runge. 2007. A cooperative partnership with the fishing industry for long time series observing of zooplankton abundance and composition in the Gulf of Maine. International Zooplankton Production Symposium: Human and Climate Forcing of Zooplankton Populations. May, 2007, Hiroshima, Japan.
- Runge, J.A. 2007. Observing effects of climate change in the Gulf of Maine: Development of a regional observing system. Maine Fisherman's Forum. Mar. 2007, Rockport, Me.

**Published reports and paper**

With the completion of the five year time series, publication of the findings and their interpretation is in progress. A listing research publications and website reports that report or interpret findings of the PULSE project is as follows:

- A summary of the time series results, including hydrography, chlorophyll a concentrations and zooplankton biomass, abundance and composition is found on the PULSE website (www. pulse.unh.edu).
- Johnson, C., J. Runge, A. Bucklin, E. Durbin, L. Incze, J. Hare and J. Link. Biodiversity and ecosystem function in the Gulf of Maine: pattern and role of zooplankton and pelagic nekton. Census of Marine Life Proceedings, Gulf of Maine Science Symposium.
- Johnson, C., J. Runge, E. Head, A. Curtis, R. Jones and C. Manning. In prep. Comparison of zooplankton community structure across seasons and latitudes along the N.W. Atlantic Continental shelf.
- Runge, J.A., A. Kovach, R. Jones, S. Tallack, J. Churchill, C. Chen, G. Sherwood, H. Howell, J. Grabowski and D. Berlinsky. In prep. Understanding climate impacts on the spatial dynamics of Atlantic cod in coastal waters of the Gulf of Maine. Prog. Oceanogr.
- R. Jones and J. A. Runge. In prep. Results of a collaborative monitoring program of coastal zooplankton and ichthyoplankton in the Western Gulf of Maine. Proceedings, Gulf of Maine Science Symposium.
- Runge, J. A., R.J. Jones and C. Manning. In prep. Population dynamics of Calanus finmarchicus in relation to trophic transfer in the western Gulf of Maine: The role of storage lipids. Limnol. Oceanogr.
- A report of the results of the information exchange meetings conducted in collaboration with NAMA (Runge and Deese 2005)
- A workshop report in which the need for fixed stations as part of a regional observing strategy has been published (Runge and Braasch 2005) and is available as a pdf document on the RARGOM website (www.rargom.org).

**Images**

Images are provided on the pulse website and a greater set of images will be made available to the Northeast Consortium by R. Jones.

**Future research/ future steps**

This project has demonstrated the feasibility of a cooperative partnership between the fishing and scientific research communities that contributes to monitoring of the pelagic ecosystem in the Gulf of Maine. The partnership has involved participation of a number of fishing boats that rotate in the collection of samples.

By focusing on weekly to semimonthly sampling at fixed stations, the Northeast Consortium program has complemented the existing Gulf of Maine monitoring activities, providing relatively high temporal frequency of observations of seasonal production cycles of phytoplankton and especially zooplankton, for which there is not another data source in the western Gulf of Maine. These data are extremely useful to coupled physical-biological model development, as they would document the timing of biological events that can be used to test model predictions and provide insight not only into the extent of interannual variability and trends in plankton biomass and structure but also in the timing of biological events in the pelagic ecosystem. The measurements of seasonal cycles in the Gulf of Maine plankton should prove useful for the interpretation of and the NMFS ECOMON and CPR plankton survey data.

A potential use of fixed station time series as an information support tool is an ecosystem management context is application to development of a combined observing and modeling strategy for forecasting effects of climate change on the dynamics of spatially structured cod populations spawning in the western Gulf of Maine. Present understanding indicates at least two genetically differentiated complexes: a late-spring spawning, coastal population centered in Ipswich Bay and a population that spawns in winter inshore and on nearshore banks in the Gulf of Maine and off southern New England. The two populations likely diverge in trophic interactions and physiological and behavioral responses to different winter and spring environments. Coupled physical-biological modeling has advanced to the point where forecasting of environmental conditions for recruitment into each of the two populations is feasible, backed by hydrographic, primary production and zooplankton data collected by local remote sensing and fixed station sampling. Forecasts of environmental influences of dispersal and growth of planktonic early life stages, combined with understanding of possible population-specific usage of coastal habitat by juveniles and differential resident and migratory patterns of adults can be used to develop scenarios for spatially explicit population responses to multiple forcings, including climate change, anthropogenic impacts on nearshore juvenile habitat and management interventions such as regional fisheries closures (Runge et al. in prep.).

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