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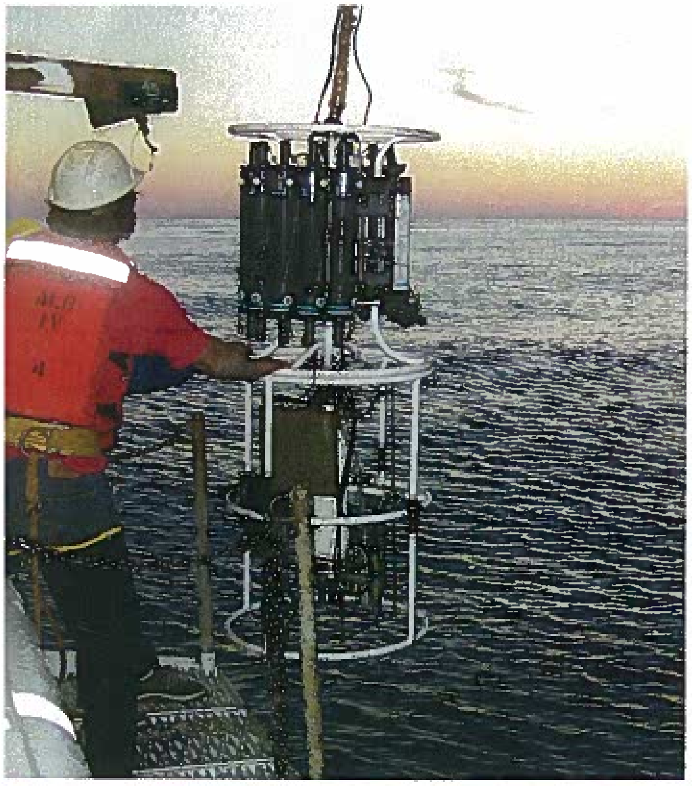

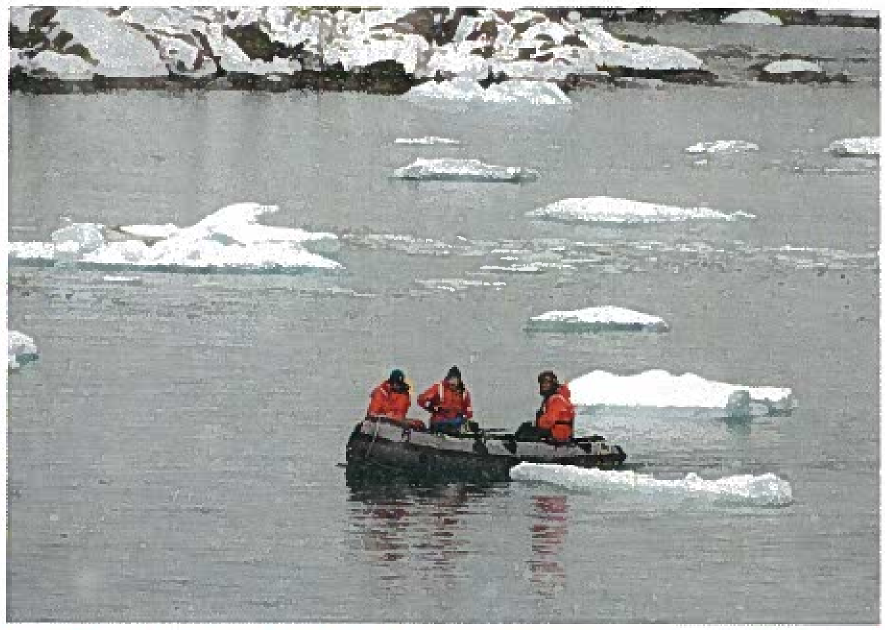

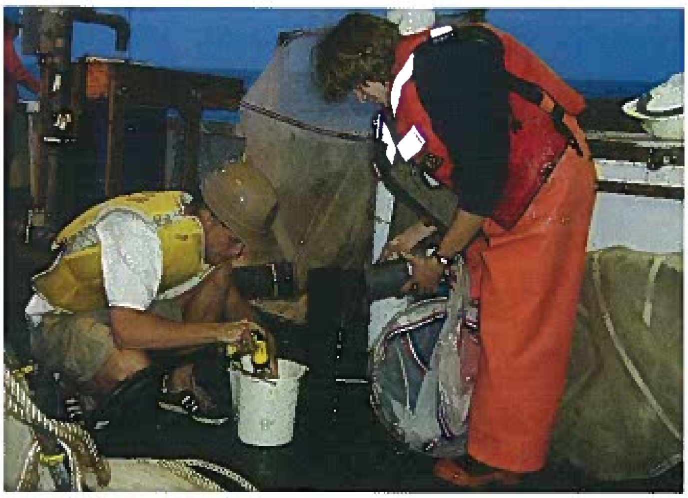

special issue featuring

THE US GLOBEC PROGRAM: CLIMATE CHANGE AND MARINE ECOSYSTEMS

The Coastal Gulf of Alaska Program: Progress and Perplexity

By Nicholas Bond

The Gulf of Alaska (GOA) is a vast (~370,000 square km),

partially enclosed basin of the North Pacific Ocean rimmed by rugged coastal terrain.

It features stormy weather frequently through much of the year, and in contrast to the California Current System (CCS; see the CCS article by Batchelder in this issue), winds generally favoring coastal downwelling. One might suppose this would imply a meager supply of nutrients, and hence an impoverished food web. On the contrary, biological productivity is high enough to support large populations of fish, seabirds, and marine mammals. This includes huge runs of pink salmon (*Onchorhyncus gorbuscha*). An overarching objective of US GLOBEC has been to determine how the feeding conditions for juvenile pink salmon (Figure 1), and ultimately their returns as adults, relate to the properties of the ocean on the GOA shelf.

The US GLOBEC Coastal Gulf of Alaska program (CGOA) employed a multi-pronged observational effort (Figure 2). As context for more detailed field measurements, a long-term observing program (LTOP) was carried out from 1997 through 2004. LTOP consisted of a series of oceanographic measurements at one to three month intervals along specified transect lines in the northern GOA. These measurements included vertical profiling of temperature and salinity, as well as analysis of water samples from various depths to determine nutrient and chlorophyll concentrations. At selected stations, net tows provided plankton samples. In a separate effort, trawl surveys using chartered fishing vessels targeted fish roughly four times a year during the summer and fall of 2001 through 2004. The LTOP cruises took place not just in the summer, when the weather is often relatively benign, but also during the stormy, cool season. Not surprisingly, there are some gaps in the data coverage due to horrific weather and a variety of logistical problems. But these gaps are relatively minor, which is a testament to the fortitude of the ships' crews and sea-going scientists. The legacy of LTOP and the trawl surveys was unprecedented information on the seasonal cycle and year-to-year variations in the physical oceanography of the CGOA and of associated biological properties.

The "snapshots" of the GOA from LTOP were complemented by continuous measurements from moored buoys for extended intervals in the period from 2001 to 2004. Although relatively few in number, the moorings sampled continuously and could fully resolve the rapid fluctuations in ocean properties with time. These moorings included sensors at a series of depths to characterize temperature, salinity, fluorescence, and current fluctuations. Selected moorings included a surface buoy with

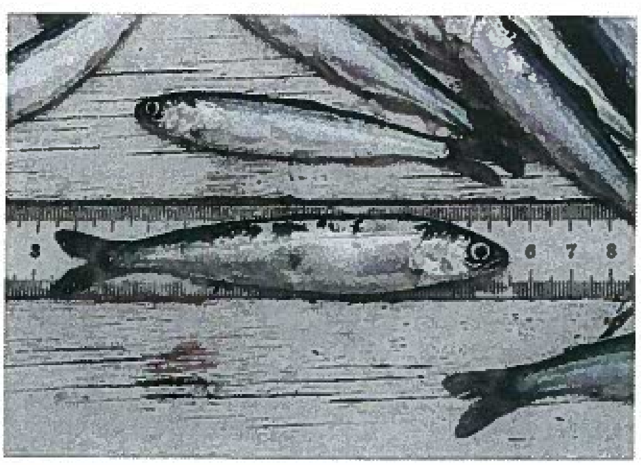

Figure 1. Juvenile pink salmon

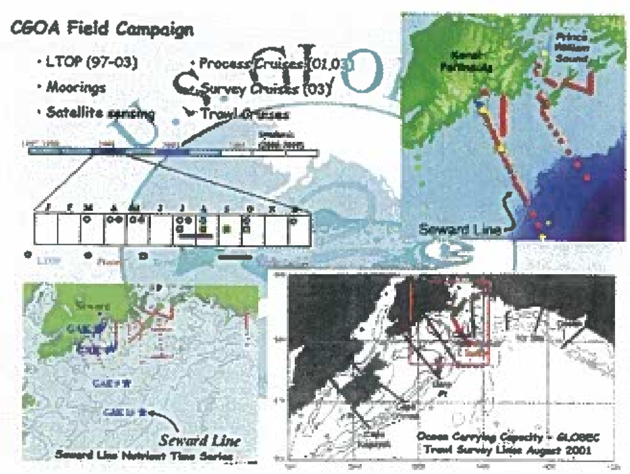

Figure 2. Summary of GLOBEC CGOA field activities. The upper left corner shows the timeline for the primary elements of the field work. The upper right portion indicates the locations of measurements from the long-term observing program (red dots), process studies (yellow dots), and moored buoys (blue and green dots). The lower left portion shows the sites with repeated observations of nutrient concentrations. The lower right corner indicates the transects for the surveys focusing on juvenile pink salmon.

weather observations and specialized instruments to monitor nutrient concentrations and rates of primary productivity at particular depths. One mooring included a TAPS-8, an innovative acoustic device that operates as a radar, to infer zooplankton distributions as a function of size and shape.

The process study portion of GLOBEC CGOA utilized a different kind of observational strategy. Process studies seek to understand the interactions or relationships between different components of the ocean system. One major set of process studies had the primary objective of measuring the feeding and growth rates of the various plankton communities on the GOA shelf, and their relationships to the regional ocean's physics and chemistry. This required running laboratory experiments at sea such as: measuring the growth rates of plankton from water samples, and collecting and preserving organisms for further analysis on land. Another set of process studies from 2001 to 2004 focused on juvenile pink salmon, with a focus on growth rates and diets across years. The organizing principle was to better understand how climate-related variability in the ocean environment impacted the feeding conditions for the salmon and, ultimately, their survival during the critical juvenile stage of their lifecycle.

The modeling portion of GLOBEC CGOA represented a mathematical means for exploring the interactions between the physical, chemical, and biological components of the system (also see the modeling article by Haidvogel and Curchister in this issue). Models also provide tangible benchmarks of our understanding; consistently good performance by a model generally indicates that the important mechanisms are being handled reasonably well. Adapting existing models for the CGOA required substantial effort. The large discharge of fresh water into the GOA represented a special challenge, and the interactions between nutrients, phytoplankton, and zooplankton characteristic of the GOA required a great deal of tuning and testing. The model development for the GOA did not have payoffs just for GLOBEC. The lessons learned here are proving valuable towards the improvement of models for other coastal marine ecosystems.

COASTAL VERSUS OFFSHORE WATERS: ECOSYSTEM IMPLICATIONS

A wide variety of research was conducted under the auspices of GLOBEC CGOA. For the sake of brevity, here we concentrate on one topic that illustrates some of the successes and remaining issues toward understanding this system. Specifically, thanks to GLOBEC, we now have a deeper appreciation for how the coastal waters on the GOA shelf differ from those farther offshore near the shelf break, and what the implications are for the biology. We focus on the summer, when pink salmon emerge from Prince William Sound and smaller embayments and must find suitable prey on the GOA shelf.

Based on physical and chemical properties, the nearshore and offshore domains of the GOA should support slow rates of phytoplankton growth in the summer. After an intense but brief spring bloom, nearshore waters are generally low in nitrate and other macronutrients necessary for photosynthesis by plankton. On the other hand, due to copious discharge from rivers emptying into the GOA, the coastal waters do tend to have relatively high concentrations of micronutrients such as iron, which is essential for certain phytoplankton, in particular, large-celled diatoms.

In contrast, offshore waters tend to have high enough concentrations of macronutrients to fuel moderate growth rates of plankton through the summer. These offshore concentrations are elevated for two reasons. First, the open GOA experiences moderate-to-strong storms on an intermittent basis from early fall through spring (during summer there are less frequent and less intense storms). The winds associated with cool-season storms mix the upper portion of the water column sufficiently to recharge nutrients near the surface, and there is usually enough wind in the summer to help in their replenishment. Second, the drawdown rate of nutrients is modest because phytoplankton abundance remains low due to grazing pressure by zooplankton. Moreover, the species of phytoplankton that thrive in offshore waters tend to grow slowly as an adaptation to low concentrations of iron, since there are virtually no sources of the latter for the deep basin of the GOA. Hence, the coastal waters are deficient in macronutrients and replete in micronutrients, and the offshore waters are just the reverse. But the chemistry is favorable for photosynthesis and abundant plankton growth where these waters mix.

This begs the question: what controls the location and magnitude of the exchange of coastal and offshore waters? The aforementioned LTOP and mooring observations supplemented by other sources of information, such as satellite-based estimates of sea surface height (SSH), sea surface temperature (SST), and surface color, revealed that water exchange is a highly dynamic and variable process. The boundary between these water masses was sometimes abrupt, (i.e., in the form of a front) and sometimes much more diffuse. The nature of this boundary was generally related to the contrast in salinity between the water masses, with fresher coastal waters associated with stronger fronts. On the other hand, we have a limited understanding of which factors determine how far offshore this boundary occurs. For example, based on measurements from moorings south of the Kenai Peninsula, the front was relatively inshore position through much of the summer of 2002 and offshore during the summer of 2003. Measurements of currents from the moorings indicated a cross-shelf component to the flow that was onshore-directed in 2002 and offshore-directed in 2003, but why the flow was so configured remains obscure. Neither wind nor weather patterns could explain the differences in the ocean flow observed between years. It has been suggested that slow-moving eddies with spatial scales of 100-200 km caused these variations. These eddies tend to propagate along the shelf break or a bit farther offshore, and while they are probably important to cross-shelf transports and exchanges for the outer domain of the shelf, it is uncertain whether they play a prominent a role for the middle-to-inner portion of the GOA shelf. Meanders in the flow on this portion of the shelf may set up more or less randomly but then perpetuate for extended periods. Similar processes seem to occur in the atmosphere, and cause persistent weather patterns of one type or another on spatial scales of 1000's of km for periods of weeks to even months. It would be useful to be able to predict the mechanisms responsible for water exchange in the transition zone on the shelf because that exchange seems to drive lower-trophic level production of the ecosystem.

The idea that physical factors control plankton community structure and productivity is not a new one, but the CGOA component of GLOBEC described these relationships in the region more completely and in more detail than ever before. Notably, a process study carried out by Suzanne Strom (at Western Washington University) and collaborators yielded a comprehensive portrait of cross-shelf gradients in macronutrients, iron, plankton growth rates, and community structure (Strom et al. 2006). Gradients in macronutrients and micronutrients influenced the response to the seasonal cycle and, presumably, also to variations in climate forcing. An important message was that one size does not fit all, in that limiting factors to growth depended on the community composition which varies across the shelf. This result was consistent with the lower-trophic level modeling studies for the region. Specifically, a modeling team led by Sarah Hinckley (at the NOAA Alaska Fisheries Science Center) found that properly simulating the distinctions between the nearshore and offshore domains necessitated separating phytoplankton into small and large groups, due to their different requirements and impacts on the lower portion of the food web (Hinckley et al. 2009). These model results were complemented by those from Jerome Fiechter (at the University of California, Santa Cruz) and collaborators, whose simulations helped to establish how important the lack of iron is to the growth of plankton in the offshore waters (Fiechter et al. 2009). The larger-celled plankton, such as diatoms, tend to have higher concentrations of fatty acids and hence, where they are abundant, the system can support higher concentrations of their zooplankton grazers requiring energy-rich diets. Since these types of zooplankton should represent favored prey for higher-trophic levels, including juvenile pink salmon, one might expect that physical conditions that favor them would prove beneficial for salmon growth and survival.

One of the more intriguing findings from the program relates to the expectation stated above. The periods dominated by a preponderance of large-cell plankton species did not necessarily represent good feeding conditions for pink salmon. In particular, a group of scientists from the University of Washington, University of Alaska, Fairbanks, and NOAA's Auke Bay laboratory found that juvenile salmon grew faster and had higher survival rates in 2002 than in 2003 (Armstrong et al. 2008). This was surprising since diets in 2002 were dominated by pteropods (Figure 3). Pteropods, despite having less nutritional value than copepods, are mucus net feeders and can take advantage of the smaller-celled plankton that are prevalent in the water of offshore origin (which covered much of the shelf in 2002)—and so it makes sense that their concentrations were relatively high in 2002. The surprise was that plankton communities characteristic of the coastal zone, not only in 2003 but also in 2001, were accompanied by cohorts of juvenile salmon in poor condition with low survival rates. The juvenile pink salmon were found to be more opportunistic feeders than anticipated, and hence their ability to catch prey (that is high for pteropods which are highly visible and tend to occur in large swarms) may be a key factor in ultimately determining feeding success.

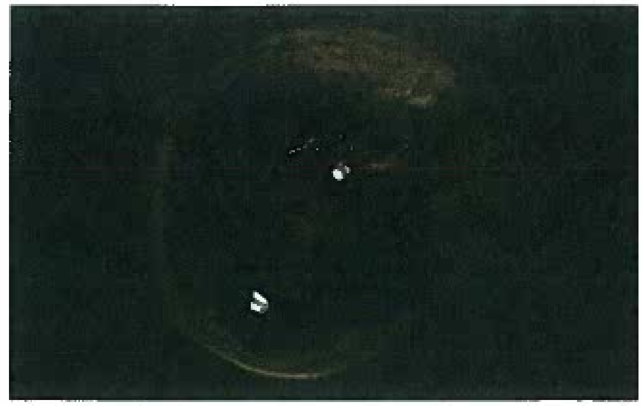

Figure 3. This pteropod was the dominant prey item for juvenile pink salmon in 2002.

As an aside, we note that increased CO_2 gas concentrations in the atmosphere are causing increased levels of dissolved CO_2 in the ocean and, ultimately, acidification of the ocean. The systematic changes that are occurring in the ocean's chemistry are liable to compromise the ability of some organisms such as pteropods to form and maintain their shells. In turn, there may be serious consequences for their predators such as juvenile salmon.

The example of water exchange between coastal and offshore zones, and resulting implications for the ecosystem, represents one of many lines of inquiry for the CGOA component of GLOBEC. It illustrates that, while we are not yet at the point where we can anticipate the full biological response to variations in physical forcing, progress has been made. It bears noting that in many ways the GOA was a *Mare Incognito* going into the GLOBEC program. So while the GOA may have yielded secrets grudgingly, we can anticipate further progress in understanding and, ultimately, predicting how the marine resources in these waters respond to the climate.

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NICHOLAS BOND, PH.D., is a senior research scientist with the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) of the University of Washington (UW). His research focuses on the weather and climate of the Pacific Northwest, and the linkages between the climate and marine ecosystems of the North Pacific. He is the chair of the executive committee of the NEP component of GLOBEC.

ADDITIONAL RESOURCES

US GLOBEC Northeast Pacific web page:
http://globec.coas.oregonstate.edu/

US GLOBEC Northeast Pacific Implementation Plan document:
http://www.usglobec.org/reports/pdf/rep17.pdf

Supplemental materials for this article available at:
www.usglobec.org/publications/CURRENT

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Figure 3: Courtesy of Matt Wilson/Jay Clark

NMEA 2011 ANNUAL CONFERENCE

Cape to Cape: In the Hub of Marine Education

Save the Dates: June 29-July 2, 2011
Conference Location: Northeastern University, Boston, MA
Hotels: Northeastern University Dormitories or Midtown Hotel

Schedule of Events:

June 27: Pre-Conference Meetings
June 28: NMEA Board Meeting, Sea Perch Workshop
June 29: Field Trips and Welcome Events
June 30-July 2: Concurrent Sessions
June 30: New England Aquarium
July 1: Thompson Island Clambake and Dancing
July 2: Auctions and Dancing
July 3: Wrap-Up Breakfast, New Board Meeting

Other Upcoming Conference Details and Deadlines:

Proposal Acceptance Notification: March 15
Advanced Registration Opens: January 11
Advanced Registration Closes: April 15
Scholarships Deadline: March 1
Scholarships Notification: March 31
Expanding Audiences Scholarship Deadline: April 15
Expanding Audiences Scholarship Notification: April 30
Traditional Knowledge Stipend Deadline: April 1
Traditional Knowledge Stipend Notification: May 1
Registration Closes: June 24