current

THE JOURNAL OF MARINE EDUCATION

Volume 27 • Number 2 • 2011

special issue featuring

The US GLOBEC Program:
Climate Change and Marine Ecosystems

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Lisa M. Tooker, Managing Editor
David Mountain, Issue Editor
Megan Garziano, Design

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CURRENT LOG *The **US Glob**al Ocean **Ec**osystem Dynamics program (US GLOBEC) was initiated jointly by the National Science Foundation and NOAA with the goal of understanding how a changing climate may affect marine ecosystems. This goal presented many challenges, scientifically, logistically... and even personally for the scientists themselves. It required coordinated studies of the physics, chemistry, and biology of large ocean areas, involving many investigators from a wide range of disciplines who had to cooperate closely in the planning, execution, and analysis phases of the program.*

The articles in this issue provide an overview of US GLOBEC, describe the four regional studies undertaken in the program and some of their results, and discuss three topics critical to the overall effort: new sampling technologies, modeling approaches, and data management. We hope this information will provide not only glimpses of the potential effects of climate change on our marine systems, but also insight into how science can address such a complex and important issue.

DAVID MOUNTAIN, PH.D., *is an oceanographer who worked at the NOAA Fisheries laboratory in Woods Hole, Massachusetts for many years before retiring in 2007. He was a Principal Investigator in the US GLOBEC Georges Bank study and a member of the US GLOBEC Scientific Steering Committee. He currently is an Adjunct Scientist with both the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts and the University of Arizona in Tucson, Arizona.*

CONTENTS

For sponsorship: The research described in this special issue was sponsored by the National Science Foundation and the National Oceanic and Atmospheric Administration

US GLOBEC: Climate Change and Marine Ecosystems

By David Mountain and Dale Haidvogel

As illustrated by the annual United Nations Climate Change conferences

(e.g., 2010 in Cancun, Mexico; 2009 in Copenhagen, Denmark; and others earlier), climate change is a major political, economic, and social issue around the world.

INTRODUCTION

Within the United States research on climate change has been ongoing for decades and has made significant contributions to the reports of the Intergovernmental Panel on Climate Change (IPCC [www.ipcc.ch]), particularly through modeling the likely effects of greenhouse gas emissions on future climate. Initially, however, there was no coordinated US research effort on how a changing climate would affect marine ecosystems—systems that provide an important source of food for society through fisheries. In the early 1990s the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA) jointly initiated the **US Glob**al Ocean **Ec**osystem Dynamics program (US GLOBEC) to gain understanding of the potential implications of climate change for marine ecosystems. The intent is for that understanding to support a more informed management and use of our marine systems. Similar programs were initiated in other countries and coordinated through International GLOBEC (www.globec.org), a core project of the International Geosphere-Biosphere Programme (IGBP). This issue of *Current* describes the US GLOBEC program and presents some of its many results.

So, how do you go about understanding 'the potential implications of climate change for marine ecosystems'? First is to recognize that the goal is not to study the climate itself. That is the role of climate scientists and climate modelers. Instead GLOBEC wants to understand the connections from atmospheric or environmental forcing—that ultimately constitute 'climate'—to the physical and biological components of marine systems. Those connections are believed to be primarily 'bottom-up'—from the atmospheric forcing, to the physical oceanographic conditions, to the lower-trophic levels (phytoplankton and zooplankton) and on up to the higher-trophic levels, including the fish stocks, particularly their early life stages which are most vulnerable to environmental conditions. The goal of the program is to develop a sufficient understanding that, given scenarios of future climate, predictions could be made, or at least insight provided, on how an ecosystem might change.

Conducting research on large-scale ocean systems presents a number of challenges. We generally cannot use the classic experimental approach or 'scientific method': observations leading to a hypothesis leading to an experiment to test the hypothesis and, upon analysis, to either repeating the experiment or revising the hypothesis. We cannot do traditional experiments since we don't control anything in the system. We are at the mercy of nature. In terrestrial systems a degree of control can be established in some situations and experiments can be conducted. But in the ocean, where the currents move the waters and mixing continually changes the waters, there is no control and, particularly, no ability to repeat specified conditions. All we really can do is observe, analyze those observations, and try to glean the desired understanding of the system.

THE PROGRAM

To confront the challenge of conducting research on large-scale ocean systems, GLOBEC chose a three-pronged approach to the research: retrospective analyses, new field studies, and modeling. Retrospective analysis refers to looking at observations that were made in the past with respect to the issues that are of interest today. Past observations, particularly from monitoring programs with long time series (decades and longer), can provide insight into relationships between changes in environmental conditions and the marine system. Past observations, however, can also be very limiting. Generally they were not made to address the current questions, so critical parameters may be missing, and the sampling may not have been at the necessary temporal and spatial scales. Still, retrospective analyses can be invaluable for identifying the types of changes and relationships that occur within a system, and raise important questions about what controls those changes and relationships; questions that need to be addressed to gain an understanding of the system's dynamics.

New field studies have been the core of the GLOBEC program's activities. In retrospective analyses, the physical and biological observations might be sufficient to develop statistical relationships between ecosystem parameters. However, those relationships likely would be dependent on the climate conditions at that time and could be dissimilar under a different climate scenario. New field studies were needed to provide a coherent, multidisciplinary sampling of the system from which process-level or mechanistic-level understanding of the connections between system components could be developed—understanding at a sufficiently basic level to be independent of the environmental conditions at the time. For the species of interest in a system this specifically involved understanding the processes controlling their growth, survival, and reproduction—the population dynamics of the species. The field studies required many researchers from a variety of disciplines working together as a team to plan and conduct the field work. A number of new sampling technologies and analysis techniques were used in the program to collect new types of information and analyze the samples and data collected in new ways—allowing us to address questions and gain understanding of ecosystems that was not possible before.

Computer modeling provides a method to bring together observations and other information into a rigorous, quantitative framework that represents how we think an ecosystem functions. Results from the field studies, retrospective studies, and previously published literature can guide how a model is structured, as well as the value of parameters controlling how the different components of the system interact within the model. Model results can be compared to observations of the system to test how well the model represents reality and, to the extent that it does not, to help identify where more knowledge of ecosystem processes is needed. A model need not address an entire ecosystem, but a variety of models can focus on different aspects of the system (e.g., how changes in circulation may affect the reproduction of a zooplankton population). Through the GLOBEC program significant advances were made in developing coupled biophysical models—models that represent the dynamics of biological populations within a geographically realistic three-dimensional flow field with realistic physical and biological properties. These coupled biophysical models ultimately can form the basis for predicting how ecosystems will respond to a changing climate.

Ecosystems contain dozens, if not hundreds, of species and it is not possible to study or model all of them. Different approaches can be taken to address this problem. GLOBEC chose to select a few target species to study in depth; species that 1) are key components of the system, 2) are likely to be sensitive to climate change, and 3) have societal importance. The species also were selected for their interconnection within a system; for example, selecting a commercially important fish species and a zooplankton species that is an important food source for the fish, particularly for the fish's larval stages. The research focus was then to study the processes—particularly the climate-sensitive processes—controlling the growth, survival, and reproduction of these species, which ultimately determine the distribution and abundance of their populations. Even with that specific focus a study would consist of a number of separate projects, each addressing some aspect of system and overall involving dozens of researchers. To be successful, the results from all of those projects need to come together in order to provide an integrated understanding of the ecosystem as a whole. Then different climate conditions could be considered and the implications for the ecosystem and the adult fish population could be estimated.

Figure 1. Location of the four regional GLOBEC study sites: on Georges Bank in the Northwest Atlantic Ocean, the California Current and the Coastal Gulf of Alaska in the Northeast Pacific Ocean, and the Southern Ocean, west of the Antarctic Peninsula.

Ecosystems are inherently variable (day-to-day, month-to-month, year-to-year), and one cannot expect to gain much understanding of how a system works by taking only a single look. Also different ecosystems differ in their structure—in their species and in how physical conditions influence those species. Comparing different ecosystems can provide deeper understanding of how systems function in general, and how the structure of a system might change under different climate conditions. GLOBEC conducted multi-year field studies in four regions: on Georges Bank in the Northwest Atlantic Ocean, in the California Current system and the coastal Gulf of Alaska in the Northeast Pacific Ocean, and in the Southern Ocean, west of the Antarctic Peninsula (Figure 1). The target species and the physical processes of primary interest in the four regional studies are listed in Table 1. The program was carried out in three phases: first, the retrospective and field studies; then a synthesis phase for each region to bring together and synthesize the results of the different projects within the region; and finally, a pan-regional synthesis phase to bring together and synthesize the key results from the different regional studies. To celebrate the program and its legacies, the US GLOBEC Final Symposium will be sponsored by the National Research Council and hosted by the American Association for the Advancement of Science in Washington DC on October 4-5, 2011.

In the following articles each regional study is described and its leading results are presented. Then three articles address other aspects of the program: new sampling technologies used in the field studies; the variety of models developed in the program; and finally, how all the data generated by the various projects

REGION	Northwest Atlantic Georges Bank	Northeast Pacific California Current	Northeast Pacific Coastal Gulf of Alaska	Southern Ocean West Antarctic Peninsula
Target Organism: Zooplankton	*Calanus finmarchicus* *Pseudocalanus* sp.	*Calanus* sp. *Euphausia pacifica* *Thysanoessa spinifera*	*Neocalanus* sp. *Euphausia pacifica* *Thysanoessa spinifera* *Thysanoessa inermis* *Thysanoessa rashchii*	*Euphausia superba* (Antarctic krill)
Target Organism: Fish	*Gadus morhua* (Atlantic cod) *Melanorammus* *Aeglefinus* (Haddock)	*Oncorhynchus kisutch* (Coho salmon) *Oncorhynchus tshawytscha* (Chinook salmon)	*Oncorhynchus gorbuscha* (Pink salmon)	*Pygoscelis adeliae* (Adélie penguins) *Lobodon carcinophagus* (Crabeater seals) *Balaenoptera acutorostrata* (Minke whales)
Physical Processes Examined	Stratification Transport/retention Cross-frontal exchange	Stratification Cross-shelf transport Upwelling/downwelling	Stratification Cross-shelf transport Buoyancy flow	Sea ice dynamics Stratification Transport/retention

Table 1. The target species and physical process of primary interest in the US GLOBEC regional studies.

were managed and have now been made available through a web-based graphical interface for all to use. A classroom activity derived from the Southern Ocean program also is presented.

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DAVID MOUNTAIN (see bio on page 1)

DALE HAIDVOGEL, PH.D., is a Professor of Marine Sciences at the Institute of Marine and Coastal Sciences (IMCS) of Rutgers University. Dr. Haidvogel founded and directs the IMCS Rutgers' Ocean Modeling Group, which has as one of it foremost goals the development, verification, and interdisciplinary application of new ocean modeling systems.

ADDITIONAL RESOURCES

For information on the US GLOBEC program:
www.usglobec.org

For information on the International GLOBEC program:
www.globec.org

Supplemental materials for articles in this issue:
www.globec.org/publications/CURRENT

PHOTO CREDIT

Figure 1: Courtesy of Fogarty and Powell, 2002

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The Northwest Atlantic Program: Climate Change and New England Fisheries

By Cabell Davis

The Georges Bank region off the east coast of New England

(Figure 1) has supported robust fisheries for over 300 years. Fishing historically has been, and today continues to be, an important aspect of the regional culture and a major contributor to the regional economy.

Climate models suggest that the Northwest Atlantic Ocean where Georges Bank is located may experience larger changes in climate over the next century than other parts of the Atlantic. The US GLOBEC Northwest Atlantic program seeks to understand the potential consequences of climate change on the Georges Bank ecosystem, with particular interest in its effects on the commercially important fish stocks in the region.

The health and abundance of a fish stock depends upon the input of new, young fish each year. These young fish are called "recruits" because they are newcomers to the population. It has long been recognized that the number of recruits each year is not simply or closely related to the number of spawning females (Figure 2). Instead for many species, like haddock on Georges Bank, some years produce large numbers of young fish, while other years produce many fewer. In 1914, a Norwegian fisheries scientist, Johan Hjort, suggested that this high variation in recruits (or recruitment) was due to changes in survival during the early life stages of the fish when they are planktonic eggs and larvae. During this planktonic period, the fish are most vulnerable to changes in their environment—the temperature, currents, available food, and predators, each of which may be affected by a changing climate. Mortality in this period is high—for a million eggs spawned, only one or two may survive to become a recruit—so even a small change in the early life mortality rate due to the environment could result in a large change in recruitment.

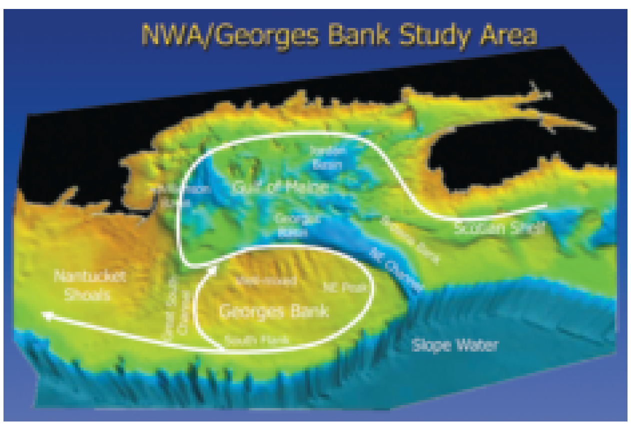

Figure 1. The GLOBEC Georges Bank study area.

Georges Bank is a shallow bank, about 300 km long and 150 km wide. The waters on the Bank are part of the southwestward flowing coastal current system that extends along the continental margin from Labrador to Cape Hatteras. More locally the waters originate from two sources: cold, relatively fresh water that enters the Gulf of Maine from the Scotian Shelf and warmer, more saline oceanic water that enters the Gulf at depth through the Northeast Channel (Figure 1). These waters mix as they flow around the Gulf of Maine and enter onto a clockwise

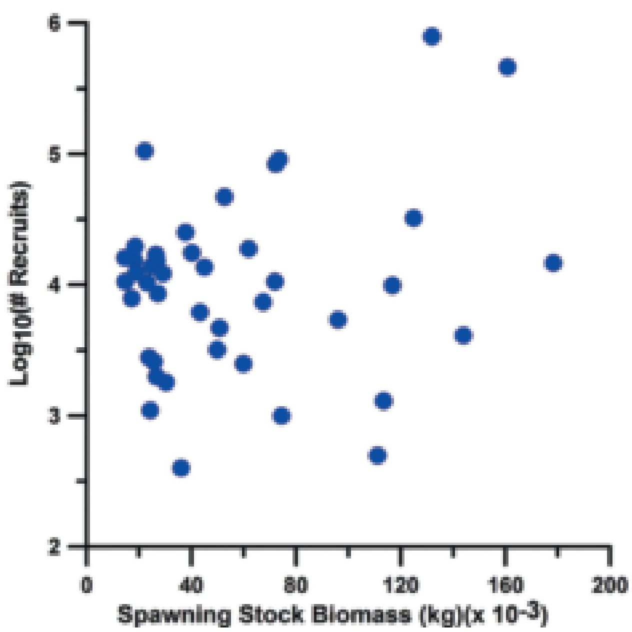

Figure 2. The $\log_{10}$ of the number of recruits versus the corresponding spawning stock biomass (combined weight of spawning females x 10^{-3} kg) for the Georges Bank haddock population from 1963-2003 (data from Brodziak et al., 2006). The recruitment is not closely related to the amount of spawning.

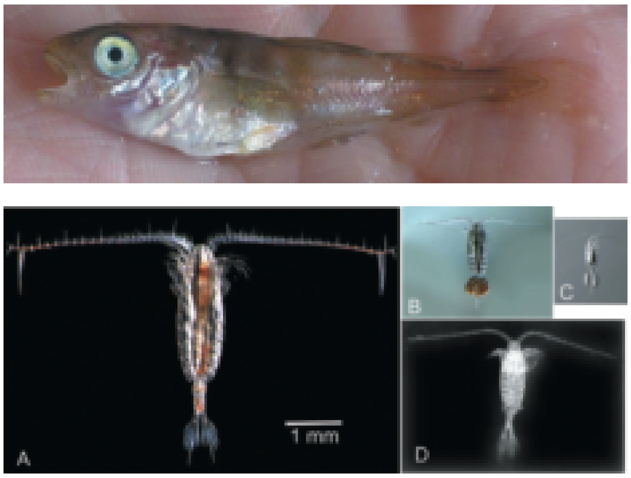

Figure 3. Larval haddock (top) and dominant copepod species on Georges Bank (bottom).

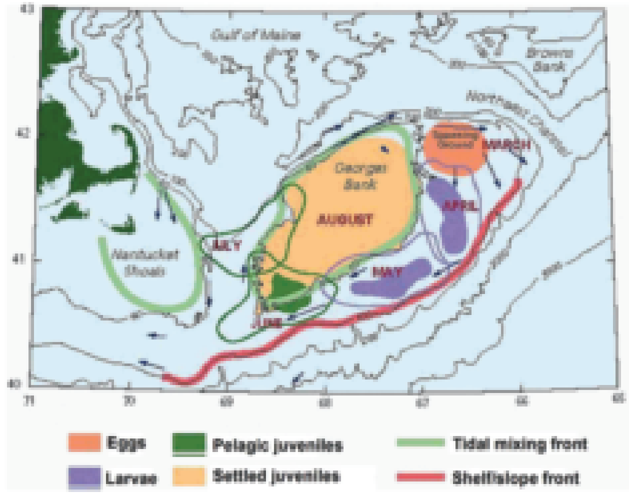

Figure 4. Spawning pattern of cod and haddock on Georges Bank.

circulation around Georges Bank. Most of the flow then continues southwestward on the shelf toward Cape Hatteras, while a smaller fraction recirculates around the Bank forming a semi-closed gyre. The shallowness of the Bank promotes strong tidal currents that mix nutrients into the photic zone, supporting a very high level of phytoplankton production. This in turn supports a high abundance of zooplankton and ultimately a high level of fish production.

The Georges Bank program has focused its investigations on the egg and larval life stages of the local cod (*Gadus morhua*) and haddock (*Melogrammus aeglefinus*) populations and on the copepod zooplankton species that are important food for the larval fish, particularly *Calanus finmarchicus* and *Psuedocalanus* (Figure 3). The goal is to understand the physical and biological processes controlling recruitment both of cod and haddock and of their dominant prey species, and how a changing climate would affect those processes. Cod and haddock spawn on Georges Bank during late winter and early spring, with spawning concentrated on the northeast peak of the Bank (Figure 4). The spawned eggs hatch and the resulting larvae drift southwestward along the southern flank of the Bank, which is rich in copepod prey at this time of year. The gyre circulation tends to retain the developing larvae on the Bank. After two to three months of growth, the larvae metamorphose to become juveniles, swim to the seafloor in the central part of the Bank, and continue their growth to become recruits to the adult population.

APPROACH AND METHODS

The research approach in this program involved historical data analysis, an ocean sampling program, and computer modeling of the ocean physics and biology. The historical data analysis included a review of data on ocean physics (temperature, salinity, currents), as well as nutrients, plankton, and fish, dating back to the 1930s. These analyses provide a long-term view of how the ecosystem has varied in response to past changes in the environment. The ocean sampling program included two types of research cruises: "broad-scale" cruises that covered the whole of the Bank to map the ocean physics and biology at monthly intervals from January to June (the growth period for larval cod and haddock), and "process" cruises to investigate specific processes or relationships between the physical conditions and the biology. The broad-scale cruises were done every year from 1995-1999. The process cruises were done in alternate years with a focus on the seasonal development of stratification in 1995, on the movement of water onto, around and off of the Bank in 1997, and in 1999 on the exchange of water and organisms across ocean frontal features that exist around the Bank. A suite of sampling equipment was used, including various plankton nets, pumps to bring water from depth to the surface for sampling, Conductivity/Temperature/Depth (CTD) profiling instruments, and a new underwater video microscope called the Video Plankton Recorder (VPR) (Figure 5; also see the technology article by Wiebe and Costa in this issue).

In addition to sampling the ocean from ships, satellite images were used to measure the color and temperature of the sea surface. The ocean color information provided data on the amount of phytoplankton in the water over the whole study region. Free drifting buoys whose positions were tracked by satellite were deployed each year to indicate how the surface waters moved. Instruments also were left for months on moored buoys to measure ocean currents, temperature, and salinity. Finally computer models were developed to simulate the ocean currents, the transport of nutrients, and the interaction of the biological populations with the physical conditions and with each other (also see the modeling article by Haidvogel and Curchister in this issue). Over 70 scientists and many more support staff were involved in the Georges Bank GLOBEC study. In all 122 research cruises were conducted with a total of 1680 days at sea.

Figure 5. Sampling systems used during the GLOBEC ocean sampling program (clockwise from the upper left): A 1-m² Multiple Opening and Closing Net and Environmental Sensing System (MOCNESS), a conductivity-temperature-depth (CTD) profiling instrument with a rosette of bottles to collect water samples, a Video Plankton Recorder (VPR), a large (10-m² net opening) MOCNESS system, a pumping system to bring water from depth to the surface for sampling, and a bongo net.

RESULTS

Early in the program researchers recognized that the salinity of the waters on Georges Bank was lower than that documented in the historic data. The decrease in salinity began around 1990 and continued throughout the GLOBEC sampling period (Figure 6). Analysis of the isotopic composition of the water, the ratio of ^{18}O to ^{16}O, indicated that the freshening had originated far to the north, at least as far as the Labrador Sea, and had traveled down the coastal current system to the Georges Bank region. It is now believed that the freshening likely originated with an increased export of low salinity water from the arctic and was associated with the large changes in arctic climate that have been documented recently.

Within the Gulf of Maine/Georges Bank region the lower salinity water was lighter than the more saline water beneath and formed a stable surface layer that inhibited vertical mixing, even in winter. Normally the spring phytoplankton bloom occurs when seasonal warming makes the surface waters lighter, reducing vertical mixing and keeping the phytoplankton in the surface layer where they have ample light for growth. With the lower surface layer salinities, the light conditions for growth could occur earlier in the year than under more normal conditions. Analysis of chlorophyll data derived from satellite images of ocean color showed that the spring phytoplankton bloom along the coast from Nova Scotia to Cape Cod did occur earlier in years when the surface water was lower in salinity.

These early blooms of phytoplankton stimulate early growth of copepod populations. GLOBEC studies found that the copepods

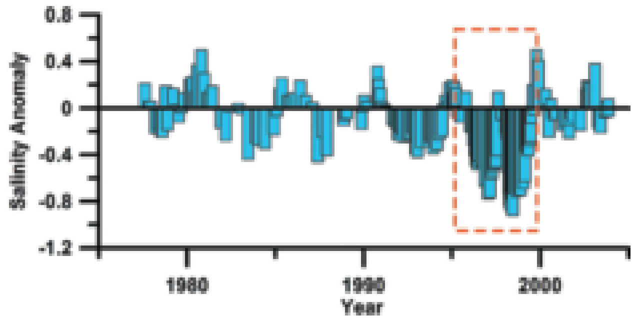

Figure 6. Salinity anomaly of the Georges Bank waters. Each bar represents the average salinity anomaly value for a different cruise or survey. The dashed red box indicates the time period of the GLOBEC field program. The anomalies were calculated by subtracting the observed salinity value from a characteristic annual cycle of salinity derived from historic data. A general decrease in salinity appears to have occurred around 1990.

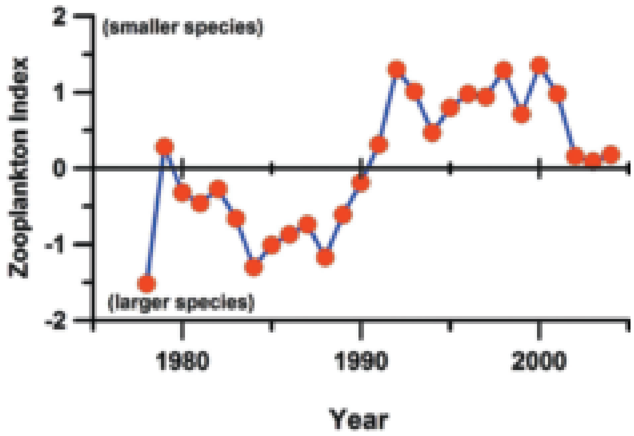

Figure 7. An index of the Georges Bank zooplankton community structure. Larger species dominate at negative index values and smaller species at positive values.

lay more eggs and grow faster in the food-rich environment of the phytoplankton bloom. The data also revealed that the copepod populations on Georges Bank, particularly the smaller-sized species, increased threefold from 1995 to 1999. An analysis using GLOBEC and historic zooplankton data showed that the zooplankton community structure on the Bank shifted from a dominance of larger species in the 1980s to a dominance of smaller species in the 1990s (Figure 7). The timing of the shift in zooplankton (~1990) was similar to that for the shift from higher to lower salinities. Other analyses have shown a similar shift in zooplankton community structure occurred in the Gulf of Maine and in the shelf waters from Newfoundland to New Jersey. The higher abundance of small copepods provided more food for the cod and haddock larvae on Georges Bank and particularly for the haddock larvae which prefer smaller-sized prey organisms than do the cod larvae. Using data from GLOBEC and other sampling done in the 1980s, the survival rate of young haddock while growing from larvae to recruits appears to have increased quite linearly with the shift in the zooplankton

Volume 27 • Number 2 • 2011

community structure from larger to small-sized species (Figure 8). Taken together the results suggest that the increased inflow of low salinity water, likely originating from changes in the arctic, influenced the phytoplankton production cycle, the zooplankton community structure, and ultimately the survival of young haddock on Georges Bank. The increase in haddock survival (by a factor of four or more in Figure 8) resulted in good recruitment for the haddock population during the 1990s, which had important implications for fishery management.

All of the physical and biological connections from the inflow of low salinity waters to the higher survival of haddock are not yet fully understood. The many projects carried out in the GLOBEC program have addressed different pieces of the overall puzzle that is the Georges Bank ecosystem. For example, satellite tracked drifters revealed how the waters on the Bank respond to strong wind forcing that can remove water, zooplankton, and larvae from the Bank (Figure 9). Controlled laboratory experiments determined the growth rates and duration of the nauplii and copepodite stages of *Calanus finmarchicus* at different temperatures and different levels of available food. These results are important for interpreting observations made in the field studies and for setting parameter values in modeling studies of the *Calanus* population dynamics. A model of larval growth rates under different environmental conditions on a section across the southern flank of the Bank was constructed (Figure 10) and its results compare well with observed rates of growth.

The analysis and modeling efforts by GLOBEC are continuing and seek to develop a capability to forecast the effect of a changing environment on the recruitment of the cod and haddock populations in the Georges Bank region. Such a capability would allow fishery managers to make more informed decisions about the future management of these important fish stocks.

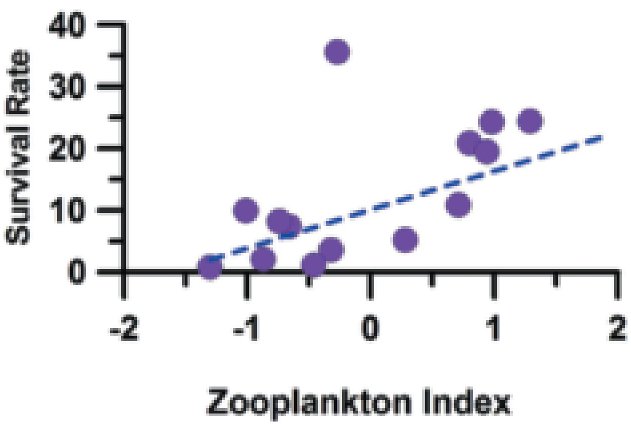

Figure 8. Annual survival index for young haddock, calculated as the ratio of the number of recruits to the initial number of larvae (x 10-6), versus the index of the zooplankton community structure (see Figure 7). The survival rate of haddock increased as the zooplankton community shifted from larger to smaller-sized species.

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CABELL DAVIS, PH.D., is a senior scientist in the Biology Department of the Woods Hole Oceanographic Institution. He has studied zooplankton throughout the world ocean and

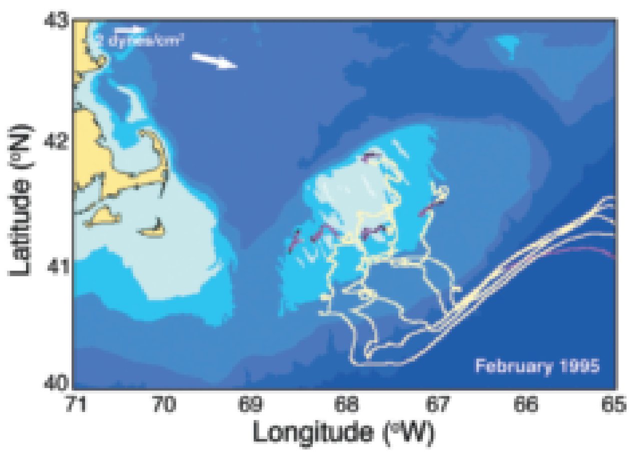

Figure 9. The movement of five satellite tracked drifters off the southern flank of Georges Bank shown here were in response to a storm event in February 1995.

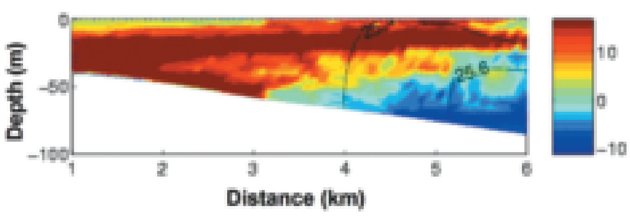

Figure 10. This shows the modeled growth rate of cod larvae along a section across the southern flank of Georges Bank. The color scale represents growth in terms of increasing weight in percent per day. The black lines represent the density of the water and show the stratification of the water column in the deeper water.

has worked in the Georges Bank region for over 30 years. He co-developed the Video Plankton Recorder, an underwater video microscope, and is currently modeling the impact of climate change on the fisheries ecosystem on Georges Bank.

ADDITIONAL RESOURCES

US GLOBEC Northwest Atlantic web page:
http://globec.whoi.edu/globec_program.html

The Northwest Atlantic Implementation Plan document:
http://www.usglobec.org/reports/pdf/rep06.pdf

Supplemental materials for this article available at:
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Figure 7: Courtesy of Mountain and Kane, 2010

Figure 10: Courtesy of Lough et al., 2006

The California Current System Program: New Insights on the Coastal Oceanography

By Harold P. Batchelder

Eastern boundary current (EBC) upwelling systems support some *of the world's highest yield pelagic fisheries, including those of the Benguela Current off Southeast Africa, the Humboldt Current off Peru and Chile, and the California Current that spans from southern Canada to Baja Mexico in the eastern Pacific.*

Because wind-forced upwelling displaces nearshore water offshore during all or a significant fraction of the year, with replacement by deep, nutrient-rich water, these areas have higher phytoplankton biomass (chlorophyll) as seen in satellite ocean color images (Figure 1). Some of the primary production is consumed by grazers, such as zooplankton, and ultimately supports a high biomass of fish and other top predators; some is carried by currents to other locations (alongshore or off the shelf); and some sinks to the seafloor where it is consumed by bottom animals or decomposes.

Upwelling regions, because of their strong linkages to the winds, may be significantly altered due to fluctuations in the climate. In the early 1990s, the US Global Ocean Ecosystems Dynamics (US GLOBEC) program began discussions of regional studies that could effectively explore the connection of climate forcing on the physical conditions, population dynamics of key species, and trophic connections in coastal systems. There was a great deal of prior knowledge of the impacts of strong interannual forcing (e.g., El Niño) on the California Current and systems further north in the eastern North Pacific. Because it is difficult to study climate effects on ecosystems in studies of a few years duration, we used shorter duration atmospheric and oceanic pertubations like El Niño-La Niña to examine the types of ecosystem changes that might be expected due to climate change. The California Current System (CCS), as an example of an EBC upwelling system off the shores of the continental US, became a region of focused observation, process, modeling, and retrospective analysis. The California Current and the Gulf of Alaska are connected through both the atmosphere (high

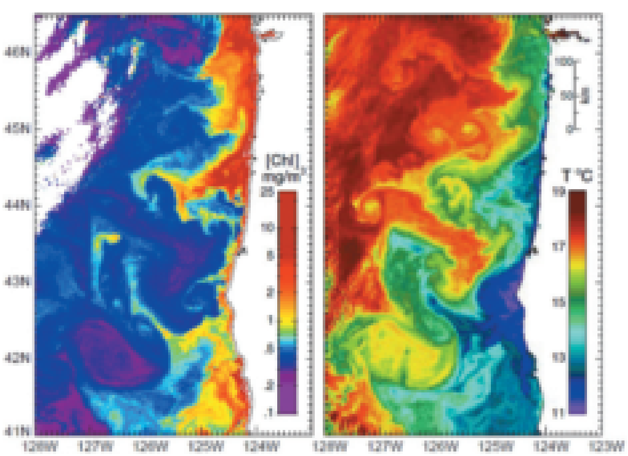

Figure 1. Left panel shows chlorophyll concentration as an indicator of phytoplankton biomass (warm colors are highest biomasses), and right panel shows sea surface temperature (warm colors for higher SST) along the US west coast on September 26, 1998.

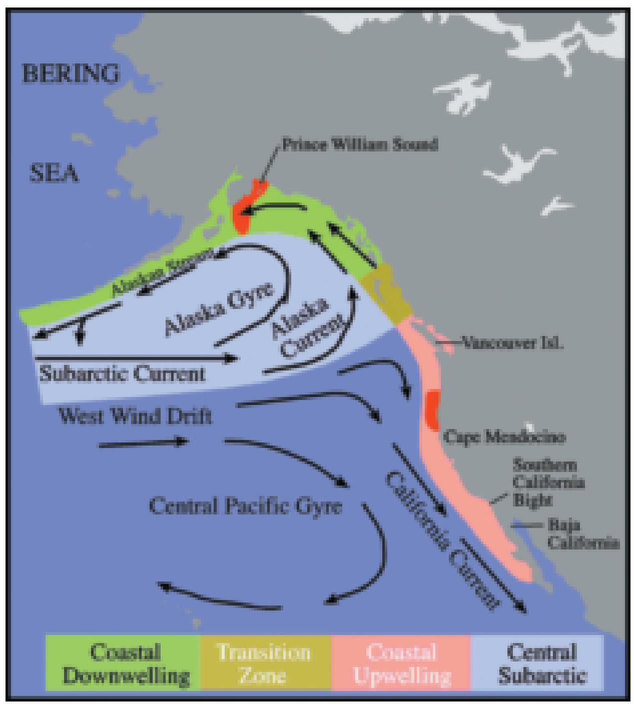

Figure 2. Fisheries production domains and large-scale ocean circulation in the Northeast Pacific Ocean. Areas in red are the locations of the GLOBEC CGOA and CCS research.

and low pressure systems) and the ocean (large-scale gyre circulations; Figure 2). GLOBEC undertook a single Northeast Pacific (NEP) GLOBEC program, with coordinated and similar ocean observations, process studies, and models in both the CCS and the Coastal Gulf of Alaska (CGOA). The program addressed three core NEP hypotheses:

1) Production regimes in the coastal Gulf of Alaska and California Current Systems co-vary, and are coupled through atmospheric and ocean forcing.
2) Spatial and temporal variability in mesoscale circulation constitutes the dominant physical forcing on zooplankton biomass, production, distribution, species interactions and retention, and loss in coastal regions.
3) Ocean survival of salmon is primarily determined by survival of the juveniles in coastal regions, and is affected by interannual and interdecadal changes in physical forcing and by changes in ecosystem food web dynamics.

In order to examine these hypotheses, a set of coordinated observations, experimentation, and modeling was conducted in these two systems over the period 1997-2004 (Strub et al. 2002). This paper is focused on the activities and findings of the research conducted by GLOBEC and other programs in the northern CCS during this period and more recently (Batchelder et al. 2002). Research in the CGOA is described in a separate article of this issue. The seasonal and annual timeline of observations and the spatial domain of the CCS research activities (Figure 3) shows the emphasis on sustained long-term observations, mesoscale mapping, and process studies focused on understanding how different components of the system—both physical and biological—interact.

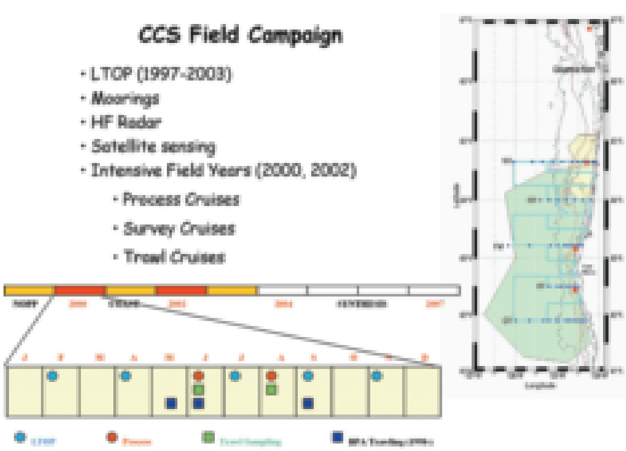

Figure 3. Spatial coverage and timeline of sampling in the California Current system (CCS). On map: yellow and light green regions in the map are the coverage of the short-range and extended-range, high-frequency radar, respectively; red dots are *in situ* moorings; dark blue dots are LTOP stations; and cyan track lines are underway sampling on survey cruises. Most intensive sampling done in May-September of 2000 (seasonal timeline shown) and 2002. LTOP sampling (five-times/per year) began in fall 1997 (pre-1999 not shown) and continued through 2003.

In controlled hypothesis testing experiments, the investigator alters the conditions among several environments, and both replication and alteration are feasible and straightforward. Statistical analysis can compare means and variation of the same response metric among the treatments. In nature, particularly in open systems lacking boundaries such as coastal Oregon, neither replication nor alteration of treatments is possible. Instead, researchers observe natural systems over several years and hope for a mix of both similar years (naturally produced replicates) and of very different years (to provide contrasting conditions). The scientist's challenge is to identify the differences among the various years and their causes. Since the processes or relationships of interest generally undergo strong seasonal cycles (e.g., winters and summers are often very different), it is important to compare similar periods of the annual cycle across years.

Environmental forcing (e.g., the winds) varied substantially during 1997-2006 and provide a rich set of conditions for exploring the links between climate and ecosystem structure and function. Notable examples include very warm conditions associated with the intense El Niño of 1997-98, rapid transition to a strong La Niña during the summer of 1998 and the subsequent persistent cold anomaly from 1999-2002, and a very late transition in 2005 from typical wintertime to summertime wind conditions. Each of these provided a new "experimental treatment," albeit without replication, with significant ecosystem effects. These large signals in the climate forcing impacted "apparent" productivity (satellite ocean color, *in situ* observations) and altered the mix of boreal and subtropical species of zooplankton (esp. copepods). In some years they dramatically altered survival of salmon; caused mismatches in the normal timing of physical and biological processes that led to catastrophic mortality and reproduction failures of marine birds and other species; and resulted in very extensive bottom-water hypoxia (low oxygen) on the shelf and deaths of near-bottom species. While the forcing of the different years represents uncontrolled "treatments," the goal of GLOBEC was to examine the physical, chemical, and biological system in sufficient detail to document the effects of the forcing on the environment, populations and ecosystem functioning, **and** to identify the responsible mechanisms. Identification of mechanisms relating atmospheric and physical processes to marine populations and ecosystem structure is important to developing predictive models capable of dealing with novel conditions that might arise with global climate change.

GENERAL OCEANOGRAPHIC SETTING

Surface currents in the deep ocean off Oregon are driven by the large-scale atmospheric wind/pressure systems. The eastward flowing North Pacific Current or West Wind Drift diverges as it nears the west coast of North America into a poleward flowing Alaskan Current along the slope of the Gulf of Alaska and an equatorward flowing California Current (Figure 2). In the Pacific Northwest, the California Current is roughly 1000 km wide and strongest in summer; the region of peak velocity is substantially offshore of the shelf-edge. Shelf currents and upwelling are forced by the local winds; and off Oregon, seasonally reversed, with northward winds and poleward downwelling flow in winter, and southward winds and equatorward upwelling flow in summer (Figure 4).

LONG-TERM CHANGE IN OREGON SHELF ENVIRONMENT

US GLOBEC chose to examine the Oregon coastal ocean because seasonal (bimonthly) oceanographic sampling along a transect extending offshore from Newport, Oregon had been done during 1961-1971. Temperature and salinity variability on seasonal and interannual time scales were well-known, but observations of chemical and biological variability in the 1960s were limited. At the conclusion of the GLOBEC Long Term Observation Program (LTOP), sufficient physical data were available to statistically evaluate two periods separated by ca. 35 years (TENOC=1961-71; LTOP=1997-2005). Surface waters (0-100 m) in summer were significantly warmer and fresher during LTOP than TENOC. Wintertime salinity and temperatures of the two time periods did not differ significantly, due mostly to larger interannual variability in the LTOP period. The significant warming of the surface waters off Oregon is consistent with similar observations further north (from Canadian Line-P) and further south (from CalCOFI hydrographic lines in Southern California), suggesting that the warming of the upper layer in recent decades occurred throughout the entire California Current. A comparison of TENOC and LTOP biological and chemical conditions was not possible because of the inadequate sampling during the earlier period.

BIOLOGICAL IMPACTS OF DELAYED SPRING TRANSITION TO UPWELLING CONDITIONS IN 2005

The potential impact of variable year-to-year ocean conditions on biological populations is illustrated using the very anomalous conditions of 2005. The spring transition from typical winter downwelling to summer upwelling occurs usually during mid-April, although the timing may vary by about a month from year-to-year. The transition to upwelling conditions in 2005 was delayed by two to three months, which meant that upwelling did not occur until after mid-June. The delayed onset of upwelling occurred along most of the US west coast north of Point Conception, California. The coastal ocean in April, May, and June had anomalously warm surface temperatures, reduced surface nutrients, lower primary productivity, and reduced zooplankton biomass. These changes altered the distribution and abundance of forage species, and reduced the nesting success of seabirds (summarized in Yoo et al. 2008).

The usually predictable seasonal renewal of nutrients through coastal upwelling is crucial to the lifecycles of many species that occupy upwelling systems. Biomass and species diversity of copepod crustaceans were anomalously low and high, respectively, typical of very unproductive conditions that occur during El Niños—but 2005 was not an El Niño year! Copepods and other small crustaceans (see photo below) are key food pathways for transfer of phytoplankton production to larger species like salmon and seabirds. Species that use the Oregon shelf for feeding and reproduction have lifecycles and timing of reproduction timed to take advantage of the high ocean productivity following the spring transition. In 2005, the delayed spring transition meant that coho and Chinook salmon that entered the oceans in April or May from freshwater habitats found an environment with unusually low productivity, with fewer and less nutritious prey that were incapable of supporting the salmon's energy needs. Salmon mortality was high and abundances of juvenile salmon in 2005 were the lowest of the eight years surveyed until that time. Fish-eating seabirds, such as common murres, had the highest summer death rates observed in 22 years of beach carcass surveys. Further south, off central California, juvenile rockfish catches were the lowest and Cassin's auklet nest abandonment and nesting failure were the highest in the more than 20 years of continuous observations. The delayed start of upwelling in 2005 created an unproductive early summer ocean that adversely affected growth and survival of many marine species.

BOTTOM HYPOXIA ON THE SHELF

In July 2002, oceanographers funded by GLOBEC documented unusually cold, fresh, and nutrient rich waters at mid-depths

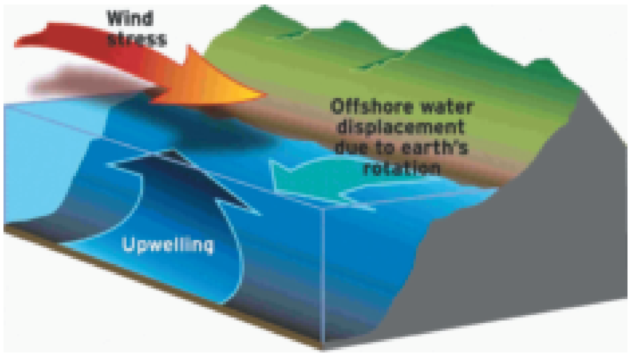

Figure 4. Schematic of coastal upwelling in the northern hemisphere (e.g., off Oregon), showing the alongshore poleward wind stress, offshore water displacement at the surface, and upwelling of deeper water, which is rich in nutrients and relatively low in oxygen.

Euphausia pacifica (krill; large shrimp-like), immature krill, and three copepods. The small spherical balls between the adult and immature krill are the eggs of adult krill.

(ca. 100 m) near the shelf break. Contemporaneously, in August near the end of the annual crabbing season, fishermen reported high incidences of dead crabs in their pots on the inner-to-middle shelf. Investigators found oxygen conditions well below the level harmful to many marine organisms (1.43 µl O_2 L^{-1}; referred to as the hypoxia threshold). Video surveys by the Oregon Department Fish and Wildlife in July 2002 revealed mostly dead fish and invertebrates in a region that has been historically teaming with bottom life. The region of bottom hypoxia covered ca. 700 km^2 between Newport and Heceta Head on the central Oregon shelf.

Spurred on by these findings in Oregon, oceanographers elsewhere found unusually cold and low salinity water at mid-depths from Canada to Southern California. Water from the subarctic Pacific had shown up off the shelf of Washington, Oregon, and California because of anomalously strong and persistent southward flow of water from the Gulf of Alaska. This "minty" water, so-called because it was cold and fresh, also was rich in nutrients and was transported onto the shelf in the onshore-directed flows at depth during the spring-summer upwelling. The upwelled nutrients fueled unusually high phytoplankton production, much of which ultimately settled to the bottom, where its decomposition contributed to the low oxygen conditions and mortality of crabs, rockfish, and other bottom fauna. The 2002 event was documented in a symposium hosted by GLOBEC NEP titled, "Cold Halocline, Hypoxia, and High Productivity in the Northern California Current."

Because of unusually strong southward transport, this late summer bottom hypoxia of 2002 was believed initially to be a one-time event. More intensive monitoring of near-bottom oxygen conditions in subsequent years has shown mild-to-severe late-summer hypoxia nearly every year. The magnitude, spatial extent and duration of bottom hypoxia varies interannually, and it is an open question how these variations are controlled by local wind forcing and more remote effects (e.g., source water characteristics).

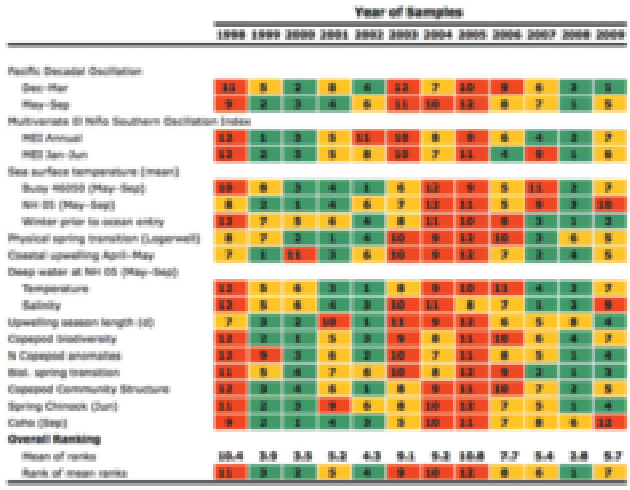

Figure 5. Ranks (1-12, where one (11) is most (least) favorable for salmon survival) of various indicators used by the NWFSC for forecasting returns of juvenile salmon (for coho one year in advance; for Chinook two years in advance) based on ocean conditions at the time that the fish enter the coastal system.

While new insights on the sensitivity of the coastal ecosystem to variability in strong wind forcing and the development of near-bottom hypoxia are emphasized here, the GLOBEC CCS project advanced our general understanding in other areas and contributed to the development or improvement of sampling tools, numerical models, and forecasting. New sampling tools, such as extended range, high-frequency radars, were deployed to provide spatial maps of surface ocean velocity fields at daily or better temporal resolution on a domain that extended beyond the continental shelf. GLOBEC scientists have been at the forefront of nesting high-resolution models into coarser resolution, larger domains to examine how basin-scale forcing impacts local-scale physics and ecosystem dynamics. The CCS component of GLOBEC has begun to have practical payoffs by

Feature	Good Salmon Survival	Poor Salmon Survival
PDO conditions (e.g., basin-scale wind forcing)	Negative	Positive
SST and water characteristics off Oregon	Cold and salty	Warm and fresh
Spring transition	Early (March-April)	Late (mid-May or later)
Upwellling season duration	Long	Short
Zooplankton composition	Cold-water species	Warm-water species
Food chain	Lipid- (energy) rich	Lipid-poor
Forage fish species abundance	Many	Few
Juvenile salmonids	Many	Few
Note: time lags may complicate interpretations of conditions		

Table 1. Conditions that provide favorable and unfavorable salmon survival. This is a subset of some of the indices shown in Figure 5.

providing operational advice to fisheries managers. Scientists from the Northwest Fisheries Science Center of NOAA used data collected by GLOBEC and other programs to identify ocean conditions that favor salmon survival (Table 1) and to develop multi-variate ocean and ecosystem indicators to forecast future salmon returns (Figure 5).

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HAROLD P. BATCHELDER, PH.D., is a Professor of Oceanography in the College of Oceanic and Atmospheric Sciences at Oregon State University. His research focuses on zooplankton ecology and coupled biophysical modeling of marine organism responses to physical processes and variability in coastal systems. He served as the coordinator of the US GLOBEC National Program Scientific Steering Committee for six years, and the Executive Director of the GLOBEC Northeast Pacific program for 10 years.

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

A photo-essay of the July-August 2000 R/V New Horizon Cruise: **http://globec.coas.oregonstate.edu/nh_photos/photojournal.html**

Spatial scales in ocean mapping classroom exercise:
http://globec.coas.oregonstate.edu/outreach/tas/classroom.html

NASA's Ocean Motion website:
http://oceanmotion.org/html/introduction-general.htm

Upwelling and downwelling wind driven circulation:
http://oceanmotion.org/html/background/upwelling-and-downwelling.htm

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

PHOTO CREDITS

Figure 1: (the processed satellite images) Courtesy of P. Ted Strub, Oregon State University

Figure 2: (redrawn from an original) Courtesy of Ware and McFarlane, 1989

Figure 4: Courtesy of the NWFSC, NOAA

Figure 5: Courtesy of Ocean Ecosystem Indicators of Salmon web page (http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm)

Page 12: Courtesy of Bill Peterson

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

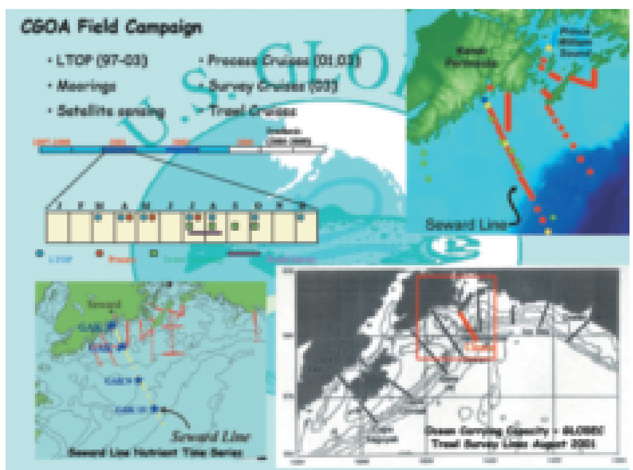

Figure 2. Summary of GLOBEC CGOA field activities. The upper left corner shows the timeline for the primary elements of the field work. The upper right portion indicates the locations of measurements from the long-term observing program (red dots), process studies (yellow dots), and moored buoys (blue 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

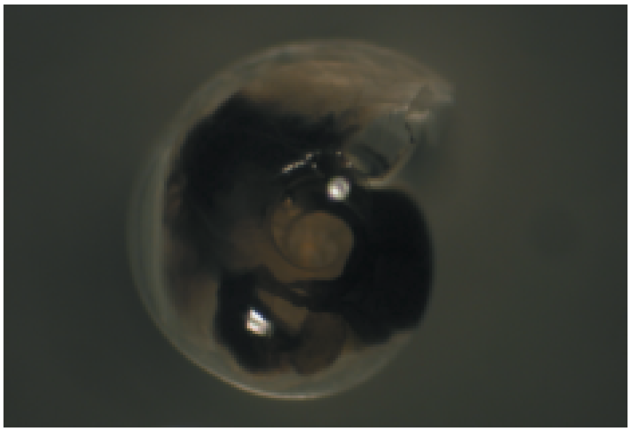

Figure 3. This pteropod was the dominant prey item for juvenile pink salmon in 2002.

(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.

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

PHOTO CREDITS

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Figure 3: Courtesy of Matt Wilson/Jay Clark, NOAA

The US Southern Ocean GLOBEC Program

By Eileen E. Hofmann, Daniel P. Costa, and Joseph J. Torres

The US Global Ocean Ecosystem Dynamics Program (GLOBEC)

selected the Southern Ocean (SO) as a study site because it was an ideal location for studying the responses of marine life to environmental change.

DEVELOPING THE PROGRAM

The International GLOBEC program designated the Southern Ocean as a priority research area, leading to a multi-national research effort that included contributions from the United Kingdom, Australia, Germany, and Korea as well as the US. Taken together, the multi-national team covered much of the ocean surrounding the world's most southern continent, Antarctica.

Over the last 25 years, the western Antarctic Peninsula region has experienced rapid warming: present-day sea ice concentrations and extent are reduced relative to those in previous decades. Moreover, the region is highly productive and supports a large standing stock of Antarctic krill (*Euphausia superba*), large populations of associated predators, and is covered by winter sea ice. For those reasons, the US SO GLOBEC field studies focused on the western Antarctic Peninsula, in particular the Marguerite Bay region (Figure 1a). Field work took place in 2001 and 2002 during the austral fall and winter, which is a crucial time of year for understanding the ecosystem. Fall and winter were the seasons we knew the least about. The field studies consisted of four survey cruises aboard the RVIB *Nathaniel B. Palmer* (Figure 1b), four process cruises aboard the ARSV *Laurence M. Gould* (Figure 1b), deployment of year-long current meter mooring arrays, deployment of year-long passive acoustic arrays, and deployment of satellite-tracked surface floats and satellite-linked dive recorders (tags) on penguins and seals. Additional program details are in Hofmann et al. (2002).

The primary objective of the US SO GLOBEC program was to understand the environmental and biological factors that contribute to enhanced Antarctic krill growth, reproduction, recruitment and survivorship, and to understand the interactions between Antarctic krill and its predators and competitors. The target species for SO GLOBEC were Antarctic krill, Adélie penguins (*Pygoscelis adeliae*), crabeater seals (*Lobodon carcinophagus*), and minke whales (*Balaenoptera acutorostrata*) (Figure 2). Those species, as well as the many other zooplankton and micronekton (pelagic fishes and shrimps) species, provided the focus for the US SO GLOBEC program. The emphasis on habitat and top predators, as well as Antarctic krill, was reflected in the program science questions (see sidebar) and was an important contribution to Antarctic marine science. The US SO GLOBEC program made many contributions to understanding the structure and function of the Antarctic marine ecosystem, some of which are described below.

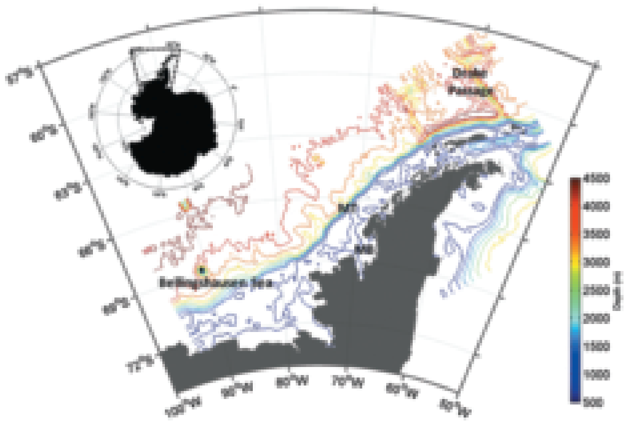

Figure 1. Map showing the location of the US SO GLOBEC field studies along the western Antarctic Peninsula. The colored lines represent bottom bathymetry in meters. The location of Marguerite Trough (MT), Marguerite Bay (MB), and George VI Ice Shelf (GVIS) are indicated. The lower panel shows the two ships used in the US SO GLOBEC field studies working in the sea ice off the western Antarctic Peninsula in the 2001 austral winter. The ship in the foreground is the Antarctic Research and Supply Vessel (ARSV) *Laurence M. Gould*, which was used for the process cruises. The ship in the background is the Research Vessel Ice Breaker (RVIB) *Nathaniel B. Palmer*, which was used for the survey cruises.

US SO GLOBEC RESEARCH HIGHLIGHTS

Interannual variability: The US SO GLOBEC field studies took place in two very different fall-winter seasons. In autumn of 2001, sea ice was late in forming and the area in and around Marguerite Bay was essentially ice-free until late June. In contrast, the region was covered with sea ice by early May in 2002, with the onset of sea ice formation being about two months earlier. The differences in the timing of sea ice formation in the two years provided a natural experiment.

For Antarctic krill, the late-forming sea ice in 2001 meant lack of a predator refugium because krill hide in the nooks and crevices on the underside of the sea ice. Also, the ice crystals associated with sea ice formation normally capture algae from the water column as they float to the surface, forming a sea ice microbial community. This community provides a fall/winter food supply for Antarctic krill that are known to feed on the underside of sea ice. The late formation of sea ice in 2001 meant that little algae remained in the water column (due to reduced light) and, as a result, sea ice algal concentrations were low. In contrast the sea ice microbial concentrations were an order of magnitude higher in 2002 because sea ice formed when concentrations of algae were still high. This difference in food supply may have contributed to poor development and growth of Antarctic krill larvae in 2001 and lower metabolism across all sizes of Antarctic krill.

The differences in sea ice cover also influenced the distribution of crabeater seals, which use the ice to rest on. They also feed in areas where the sea ice edge concentrates prey. When the sea ice concentration was less than 50%, crabeater seals selected areas of high ice cover and avoided regions of open water. With increased availability of sea ice, the crabeater seals remained within ice covered areas, tended to use areas of medium ice coverage (30–50%) earlier in the winter, used areas of higher coverage (90%) later in the winter. They avoided areas where there was total sea ice cover as they could not gain access to the water. Thus results confirmed that crabeater seals are dependent on sea ice and that as sea ice declines with climate change their habitat will decline (see Costa et al. 2010).

Antarctic krill: A primary research goal was to evaluate the relative importance of overwintering strategies of Antarctic krill, particularly in its larval stages. Ship-based laboratory studies completed during the 2001 and 2002 field studies tested the relative contribution of five proposed overwintering strategies: body shrinkage, feeding on sea ice algae, carnivory, using lipid stores, and reduced metabolism. Evidence was found to support each of the overwintering mechanisms, leading to the conclusion that the availability of a suite of overwintering strategies provides Antarctic krill with flexibility in the options that allow survival.

Another research goal of the US SO GLOBEC program was to determine the winter abundance and distribution of Antarctic krill in the Marguerite Bay region. This was done using ship-based sampling with a variety of nets, the most important of which were the 1-m^2 and 10- m^2 **M**ultiple **O**pening and **C**losing **N**et and **E**nvironmental **S**ampling **S**ystem (MOCNESS; Figure 3), which captured small and large species, respectively. These nets allowed sampling of multiple depths while simultaneously recording salinity, temperature, and depth. Nets were used in tandem with hydroacoustic surveys (sophisticated fish finders). The net samples provided detailed descriptions of the zooplankton and micronektonic community assemblage at

Figure 2. Key species that were the focus of the US SO GLOBEC field studies. Clockwise from upper left: Adélie penguins (one to right has a satellite tag attached); Antarctic krill; crabeater seal with satellite tag attached; ARSV *Laurence M. Gould* in background; Adélie penguin with chick on nest; minke whale in an opening in the ice pack; and a crabeater seal.

Figure 3. Deployment of the 10-m^2 MOCNESS system to capture zooplankton and the small fishes and shrimps known as micronekton. The MOCNESS system has six nets that are deployed in sequence during the course of a single tow. It communicates with the ship via the cable it is towed with, so its depth is known at all times, which is important for knowing when to change the nets. The system provides detailed information on what species are present, how many there are, and how deep they live.

specific locations. Important conclusions from the net-based surveys included substantial increases in micronekton community biomass from 2001 to 2002 and evidence of a successful recruitment year for krill in 2002.

The hydroacoustic surveys provided continuous measurements of acoustic backscatter (sound reflected from organisms) patterns along ship track lines that were converted into biomass and abundance estimates for particular species, such as Antarctic krill. The acoustic backscatter observations showed large seasonal changes in zooplankton abundance with an order of magnitude decrease in winter. The combined environmental and acoustic backscatter data set allowed description of the space and time distributions of aggregations of Antarctic krill and the relationship of those to habitat structure. An important finding was that winter aggregations of Antarctic krill were found along the inner continental shelf in areas characterized by reduced current velocities and the presence of ocean water known as Circumpolar Deep Water (see Lawson et al. 2004 for details).

Seals, penguins, and whales: The suite of important predators studied during the US SO GLOBEC program required a range of approaches to describe their distribution, abundance, movement patterns, condition, and prey. Analysis of those data are providing new and exciting information on how predators interact with their environment and their role in the SO marine food web. For example, one new and exciting result was the identification of 'biological hot spots', or regions of high predator abundance in and around Marguerite Bay.

During the US SO GLOBEC field programs, pinnipeds were studied using two fundamentally different approaches. The first measured the abundance and distribution of all pinnipeds using standard line-transect visual surveys. The second used tags placed on crabeater seals to provide information on their diving behavior and movement patterns. The visual surveys showed the presence of several seal species (crabeater seals, leopard seals [*Hydrurga leptonyx*]), Weddell seals (*Leptonychotes weddellii*), southern elephant seals (*Mirounga leonine*), and Antarctic fur seals (*Arctocephalus gazella*)], but crabeater seals were the only ones present in large numbers. The tracking data (Figure 4) indicated that crabeater seals were most commonly found in the nearshore regions where the change in bathymetry was greatest, and where there was heavy, but not complete, sea ice cover. During the fall and winter, the tagged crabeater seals made long, deep dives, focusing their foraging effort during the day. This was markedly different from previously reported summer behavior where seals foraged primarily at night in the upper 50 m of the water column.

Physiological studies showed that crabeater seals were in good condition (body mass and fat stores) during the fall and winter and that their mass and fat content actually increased between those seasons. This confirmed that crabeater seals successfully forage during the period of greatest winter darkness and highest sea ice cover. A surprise finding was that

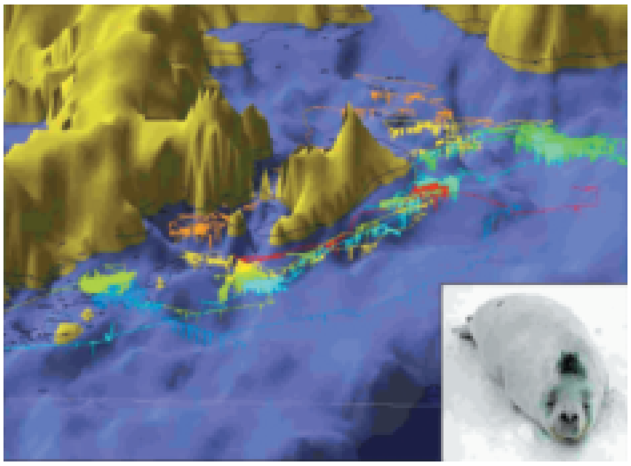

Figure 4. The tracks of individual seals (denoted by different colors) obtained from satellite-linked dive recorders (tags) placed during the SO GLOBEC field studies. The tags show that these animals remained in the Marguerite Bay region during winter and tended to stay in specific locations for extended times. The depth of individual dives is indicated by the curtain effect. The individual tracks show that animals did more diving in areas of variable bathymetry. A crabeater seal with an attached tag is shown in the inset.

in addition to their primary prey of Antarctic krill, crabeater seals also consumed fish. These seasonal differences may reflect the overwintering behavior of Antarctic krill, or result from competition with other krill predators that were common in areas favored by crabeater seals.

Adélie penguins, also outfitted with satellite tags, were found to forage over the deep troughs that cut across the continental shelf even in winter, suggesting these areas may represent true regional 'hot spots'. Adélie penguins do not forage at night, hence remaining close to areas of high prey concentrations may be a strategy to deal with the limited foraging time imposed on them by the short length of winter days.

The distribution and abundance of cetaceans were assessed using standard line-transect visual survey methods and a variety of acoustics methods. The visual surveys showed that humpback (*Megaptera novaeangliae*) and minke whales were the most commonly sighted species; and both were found in coastal habitats, particularly fjords, where complex bathymetry likely concentrates prey. The humpback and minke whale distributions were found to be influenced by the distribution of their prey (primarily Antarctic krill), certain bathymetric features, and the distribution of sea ice and Circumpolar Deep Water.

The presence of cetaceans was assessed using acoustic data recovered from expendable sonobuoys deployed during the survey cruises, and from acoustic recording packages (ARPs), which were deployed on moorings for two years, with one functioning for four years. The ARPs recorded calls from blue (*Balaenoptera musculus*), fin (*B. physalus*), humpback and minke whales, and crabeater seals, and a number of unidentified species. The sonobuoys detected calls from all of the species recorded on ARPs, as well as calls by sperm (*Physeter macrocephalus*), killer (*Orcinus orca*) and beaked (*Ziphius* sp.) whales, and Weddell seals. These datasets documented the year-round presence of blue whales and the seasonal presence of calling fin whales (Širovic et al. 2004). Call frequency of both species was lower in areas of heavy sea ice cover.

NEW IDEAS AND FUTURE DIRECTIONS

Results from the US SO GLOBEC program are providing new understanding of how Southern Ocean marine ecosystems work. Revisions in understanding of Antarctic food webs are underway because of the recognition that organisms other than Antarctic krill can sustain the suite of top predators. Fish and other zooplankton species in the food web are being investigated as a potential alternative prey for a system that is now undergoing modifications as a result of climate change. Changes in sea ice extent and concentration are an integral part of the modifications ongoing in the food web. What these effects might be is unknown at present, and the data and food web models from the SO GLOBEC program provide a framework for testing possible scenarios.

The SO GLOBEC results showed that regional environmental and biological interactions respond to processes that are occurring at larger scales. This understanding resulted in development of the Integrating Climate and Ecosystem Dynamics (ICED) in the Southern Ocean Program, which is a new international initiative, focused on integrated circumpolar analyses of Southern Ocean climate and ecosystem dynamics. Understanding variability at a circumpolar scale is basic to understanding ecosystem effects resulting from long-term and large-scale climate change. The knowledge and lessons learned from the SO GLOBEC program provide a strong basis for continuing into this next phase of Southern Ocean research.

ACKNOWLEDGMENTS

The US participation in the SO GLOBEC field program and follow-on synthesis studies were supported by the National Science Foundation (NSF) Office of Polar Programs (OPP). This article draws upon the scientific results provided by many investigators in the US SO GLOBEC program. Their efforts, insights, and commitment to quality science are gratefully acknowledged.

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EILEEN E. HOFMANN, PH.D., is a Professor in the Department of Ocean, Earth, and Atmospheric Sciences at Old Dominion University. Her research focuses on understanding the complexity and interactions in marine food webs and relating this to environmental processes and variability. She is currently the Chair of the Integrated Marine Biogeochemical and Ecosystem Research Project of the International Geosphere-Biosphere Program. She is a past member of the US and International GLOBEC Science Committees and served as Chair of the Southern Ocean GLOBEC program.

DANIEL P. COSTA, PH.D., is a Distinguished Professor of Ecology and Evolutionary Biology at the University of Santa Cruz and holds the Endowed Chair in Ocean Health. His research focuses on foraging ecology, energetics, diving behavior, and physiology of marine mammals and seabirds. He is a Fellow of the California Academy of Sciences. He is a past member of the US GLOBEC Science Committee and currently serves on the Southern Ocean GLOBEC science committee.

JOSEPH J. TORRES, PH.D., is a Professor in the College of Marine Science of the University of South Florida. His research focuses on the ecology and physiology of pelagic species from polar, temperate, and tropical regions, in particular, their adaptations to temperature and deep-sea life. He is a past member of the US GLOBEC Science Committee and currently serves on the Southern Ocean GLOBEC science committee. He is a Fellow of the American Association for the Advancement of Science.

ADDITIONAL RESOURCES

A blog and pictures from a cruise to the western Antarctic Peninsula to study Antarctic silverfish (*Pleuragramma antarcticum*):
http://www.marine.usf.edu/physiolab or **http://www.tampabay.com/specials/2010/reports/antarctic/**

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

Information on Integrating Climate and Ecosystem Dynamics (ICED) in the Southern Ocean Program:
http://www.iced.ac.uk/

Real-time tracks of the migratory patterns of mammals in the Southern Ocean and marine mammals, seabirds, sharks, turtles, and fish vertebrates in the North Pacific can be found at **http://www.topp.org**, as well as blogs and pictures from past and recent work.

PHOTO CREDITS

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US SO GLOBEC SCIENCE QUESTIONS

The science questions that provided a framework for the US SO GLOBEC field activities were focused on understanding zooplankton and top predator population dynamics and linkages of these to environmental variability.

ZOOPLANKTON SCIENCE QUESTIONS

1. What key factors affect the successful reproduction of krill between seasons?
2. What key physical processes influence krill larval survival and subsequent recruitment to the adult population between seasons?
3. What are krill's seasonal food requirements in respect to energetic needs and distribution and type of food?
4. What are the geographical variations in krill distribution in relation to the between and within season variability in the physical environment?

TOP PREDATORS SCIENCE QUESTIONS

1. How does winter distribution/foraging ecology relate to characteristics of physical environment and prey?
2. How does breeding season foraging ecology relate to abundance/dispersion and characteristics of krill?
3. How does year-to-year variation in population size and breeding success relate to distribution, extent and nature of sea ice and krill availability, and cohort strength?

Interdisciplinary Modeling in US GLOBEC

By Dale Haidvogel and Enrique Curchitser

The premise underlying the US GLOBEC program is that the global *climate system influences regional ocean processes and ecosystems in significant ways.*

The principal objective of US GLOBEC research is to understand the effects of global climate change on ocean ecosystem dynamics and, ultimately, to contribute to the management of living marine resources. In particular, US GLOBEC seeks to develop the tools needed to *predict the responses of populations and ecosystems to climate change and variability.* This goal is met through the development of "models."

The Merriam-Webster dictionary offers 14 separate definitions of the noun "model." These include two familiar ones: "a … miniature representation of something" (e.g., a model airplane) and "a person or thing that serves as a pattern for an artist" (e.g., one who poses for a painter). There is also the following less familiar definition: "a system of postulates…presented as a mathematical description of an entity…; also, a computer simulation based on such a system." Our examples below illustrate this latter meaning within US GLOBEC.

MODELING IN THE CONTEXT OF US GLOBEC

Within US GLOBEC models have two prominent roles. The first is to synthesize the observations available to US GLOBEC scientists. Despite substantial progress on observing systems, we are not able to fully observe the earth system. This is particularly true of the oceans below the sea surface. (Satellite systems are increasingly capable of observing properties at the ocean surface.) Models are therefore needed to combine relatively sparse ocean observations into a more complete picture of the ocean state.

A second role for models within US GLOBEC is to predict future states of the climate system, including its oceanic ecosystems. An observations-based description of the ocean state today and in the recent past, while a necessary precursor to prediction, is not sufficient in itself to estimate future states. Mathematical and/or statistical models with predictive capability are necessary to produce such estimates.

In US GLOBEC, our goal is a model capable of providing information on future changes in regional ocean ecosystems for use in management decision-making. Such a model would be comprised of several components, including models for the future state of the *ocean circulation*, its *chemical and nutrient fields*, and the *life histories* of one or more species of interest (the green boxes in Figure 1). These models typically take the form of systems of mathematical equations based on Newton's laws of motion for the physics (F=ma) and on observed biological relationships for the biology. Heavy arrows in Figure 1 indicate the flow of information among these components. For example, component models produce predictions for the ocean currents (the *circulation model*) and for the ocean food fields (the *ecosystem model*), and these in turn pass information to an *individual-based model* to follow the development of one or more fish populations.

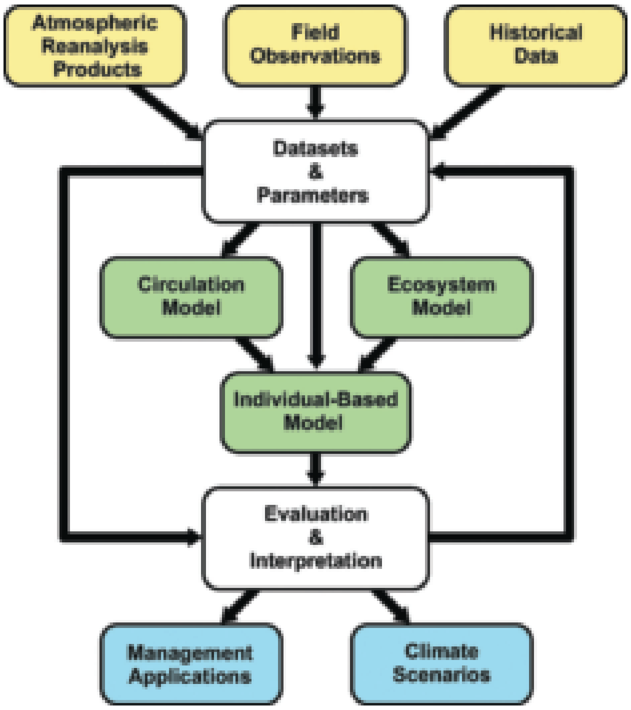

Figure 1: Overview of the components in an end-to-end coupled physical/biological model being developed within the US GLOBEC program.

These equations are functions of both space (in three dimensions) and time, as well as any parameters characterizing the ocean state (mixing rates, chemical and/or biological rates, fish growth rates, etc.). In general, we are not able to solve these equations exactly. Rather, we must find approximate solutions to the equations using a computer. In doing so, the space and time domains of interest are subdivided into finite intervals, the *grid spacing* and *time step*, respectively, and approximate solutions to the exact equations are then determined at these discrete space/time locations. This subdivision is necessary because our computer systems can represent only a limited number of oceanic variables at any one time.

The spatially subdivided equations are advanced in time, one time step at a time, to obtain the future ocean state. To do so, various data inputs are required, as suggested in Figure 1 (the yellow boxes). For example, the initial state of the ocean must be prescribed (the *initial conditions*), along with any *external forces* (e.g., the wind stress and solar radiation, in the case of the ocean). The result of this time-stepping process is a set of snapshots of the ocean state. These snapshots may then be stored for later analysis. Many parameters in this system (well, actually, all of them!) are uncertain to a greater or lesser degree. (Physical rate constants tend to be less uncertain, while the biological rate constants are in many cases very poorly known.) As a consequence, multiple simulations are often necessary to assess sensitivity to uncertainties in input parameters.

The highly simplified schematic depicted in Figure 1 hides many details. For instance, consider the *circulation model*. In its most highly evolved form, this may be a fully global, coupled climate model with multiple components (Figure 2). The model incorporates sets of equations for the atmosphere, land, and sea ice as well as the ocean. Many additional parameter values

Figure 2: Schematic of an Earth System Model used to study climate and ecosystems. Ovals represent the main model components. The red oval is a flux-coupler which coordinates communication among components. The orange rectangles are software drivers that control each component and interfaces with the coupler (e.g., controls the global and regional ocean models). The economic and social models (yellow ovals) can be used to study the role of anthropogenic activities in the climate system. The colored arrows indicate the flow of information among components. Arrow colors match the source component.

(not all of them well-known), forcing functions, and computer resources are required to solve the resulting sets of equations.

A final dilemma: the modeling system depicted in Figure 2 must be *global in extent*, but finely enough subdivided in space to *resolve regional features of particular interest* (e.g., biologically important processes on narrow continental shelves). A straightforward approach would be to subdivide the entire global ocean at uniformly fine spatial resolution. Unfortunately, the resulting problem is computationally intractable. U.S GLOBEC researchers have pioneered two alternative approaches: *nested grids* (multiple overlapping grids of varying resolution; shown schematically by the blue boxes in Figure 2) and *unstructured grids* (a single grid with smoothly varying, non-uniform spatial resolution).

THE CONTRIBUTIONS OF US GLOBEC

The development and application of coupled circulation/ecosystem models has been a central theme in the US GLOBEC program from its inception. Accordingly, contributions in this area are a central legacy of the program and an important measure of its success.

The progress made in US GLOBEC has taken many forms. First, US GLOBEC scientists have contributed to the development of fundamental modeling tools that represent the ocean and its physical, chemical, and biological state (cf, Figure 1). Many of these tools have been widely exported to the scientific community for use outside of the GLOBEC program. As an example, the two *circulation models* in primary use within US GLOBEC—the Regional Ocean Modeling System (ROMS; http://www.myroms.org/) and the Finite Volume Community Ocean Model (FVCOM; http://fvcom.smast.umassd.edu/FVCOM/index.html) —have extensive international user communities. Other advanced modeling tools—e.g., for the marine food web, for the movement and growth of various oceanic species, and

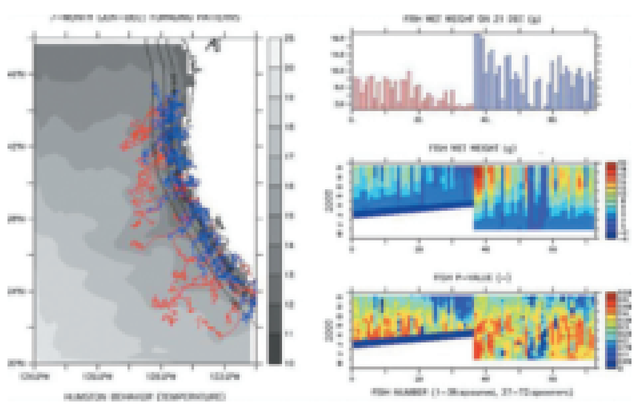

Figure 3: Modeled movement of individual sardines: temperature contours and individual fish trajectories (left); and results for 72 individual fish (right), with the weights at the end of the model simulation (top), the history of individual weight (middle), and the fraction of maximum possible consumption by each fish (bottom).

biological data assimilation—have also been pioneered by US GLOBEC scientists.

As a consequence of these advances, end-to-end modeling systems such as those shown in Figures 1 and 2 are now a reality, representing powerful new opportunities for anticipating ocean ecosystem response to changes in global climate. Figure 3 gives an example of the types of information that these new systems will be able to provide. Information from a coupled circulation-ecosystem model has been provided to an individual-based model (IBM) for sardines. The IBM then computes the movement of the sardines (a response to both ocean currents and fish behavior) as well as their growth and eventual mortality (due to natural aging and/or fishing pressure).

Such models may be applied both under contemporary and anticipated climate conditions to predict changes in fish abundance, health, and spatial distribution. Management decisions (e.g., the setting of fishing quotas) may then be made in a firmly grounded ecosystem context.

DALE HAIDVOGEL (see bio on page 4).

ENRIQUE CURCHITSER, PH.D., is an oceanographer based at Rutgers University. His interests reside at the intersection of climate and ecosystems. His current projects address topics including the role of Eastern boundary currents in the global climate system, the downscaling of climate scenarios in the Bering Sea, and the low-frequency fluctuations in the global sardine populations.

ADDITIONAL RESOURCE

Supplemental materials for this article are available at: **www.globec.org/publications/CURRENT**

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Technology Developments in US GLOBEC

By Peter H. Wiebe and Daniel P. Costa

The world's oceans are vast, largely dark, and inhospitable *environments. They are difficult to study because they are largely inaccessible. From the deck of a research vessel, one can view its surface or from submersibles or while SCUBA diving briefly glimpse its interior.*

The ocean-going ecologist is faced with the fact that he/she cannot "see" into this fascinating three-dimensional habitat and visualize the spatial arrangement and behaviors of the organisms living there. Contrast this with the terrestrial ecologist who can stroll through the forests, meadows, savannas, or deserts, viewing holistically the structural complexity of the ecosystem and the existing patterns of organisms in relation to their environment. Thus from the very beginning of biological oceanography, more than 100 years ago, instrumentation has played a fundamental role in enabling marine scientists to remotely sense the environment and to collect the organisms for their studies. Many of the advances in our understanding of the creatures inhabiting these largest of the world's ecosystems have come on the heels of the development of new instrumentation—and this was especially true for the US GLOBEC program. Electromagnetic radiation in the form of visible light and high-frequency sound are the principal forms of energy being used to create surrogate "eyes" into the sea. Although seawater transmits visible light poorly because it is absorbed, scattered, and reflected far more than in air, increasingly powerful video and camera chip technology has made it possible to develop sophisticated optically based sensors for the imaging of zooplankton close (a meter or two) to the light source. Transmission of sound in the moderate to high frequency range (38 to 1000 kHz) occurs over much greater distances and can be used for detection of zooplankton and larger animals 10's to 100's of meters from the sound source.

It was recognized before the US GLOBEC field programs started that the existing sampling technology was not sufficient to meet the program's objectives, which included sampling species of zooplankton targeted for indepth study and their predators and prey, and to measure important environmental variables concurrently. As a result, a number of new sampling tools and techniques were developed to complement existing technologies in order to carry out the field work based on ships and moorings. In some studies, new innovative tags were placed on large mammals and sea birds to acquire environmental data as well as information about the animal's location and behavior. In this way, the animals themselves serve as data gatherers.

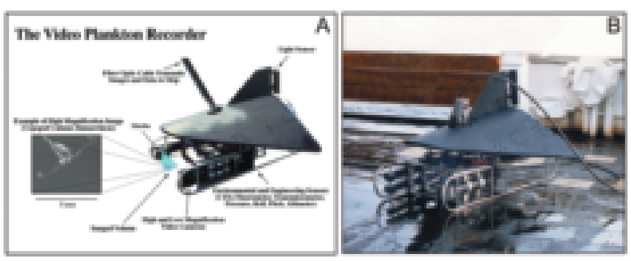

Figure 1. (a) A schematic of a two-camera VPR mounted in a towed V-fin as it was deployed on Georges Bank during process cruises. (b) The two-camera VPR ready for deployment.

OPTICAL SYSTEMS

Several optical sensor systems were used in the US GLOBEC field programs to study the distribution and abundance of zooplankton and fish eggs and larvae. We highlight one, the Video Plankton Recorder (VPR) that was developed during the GLOBEC program.

VPR: The Video Plankton Recorder is a high-magnification underwater video microscope that provides images of plankton undisturbed in their natural orientations (Davis et al. 2005). The original VPR had four analog video cameras and a strobe light; each camera imaged concentrically located volumes of water ranging from less than 1 ml to 1000 ml, but it was subsequently modified to a one- or two-camera system (Figure 1). The systems used typically had a volume imaged of about 5.1 ml at a rate of 60 images per second (i.e., a sensing volume of about the size of a medium cup of coffee). An image processing system was also developed that was capable of digitizing each video field in real time and scanning the fields for targets using user-defined search criteria such as brightness, focus, and size (Hu and Davis 2006). The targets are identified using a computer program that automatically identifies major zooplankton groups (and in some cases, species) based on their optical characteristics. This provides near-real-time maps of the zooplankton distributions. Targets that meet the criteria are sorted into different taxonomic categories, enumerated, and measured together with the location, time, and depth at which they were observed. The VPR has typically been deployed as the primary zooplankton sensor along with environmental sensors in an underwater vehicle that is towed from the ship and undulated from the surface to some depth (100 m or greater) in what is often called a "towyo."

ACOUSTIC SYSTEMS

High frequency acoustics played a significant role in a number of the GLOBEC field programs. Several different acoustic systems were used. The two fundamental measurements relevant to the acoustic detection of zooplankton are volume backscattering (integration of the energy return from all individuals in a given ensonified volume, i.e. echo integration) and Target Strength (TS: echo strength from an individual). One echosounder used in surveys of Georges Bank and the Gulf of Maine, and in the Southern Ocean was BIOMAPER-II (Figure 2). It carried multiple frequency sonar with pairs of up/down looking split-beam transducers operating at 43, 120, 200, 420, and 1000 kHz (Wiebe et al. 2002). It also carried a VPR and an environmental sensing system that measured pressure, temperature, salinity, depth, fluorescence, and turbidity. Together these sensors enabled the distribution and abundance of zooplankton to be assessed on scales much finer than can be achieved with net systems.

Figure 2. BIOMAPER-II being recovered from a tow between stations 62 and 63 west of Alexander Island on RVIB Nathanial B. Palmer cruise 0104 (top). The vehicle operates to depths of 300 meters at speeds of 4 to 6 knots. BIOMAPER-II being moved into a heated van for storage after the tow between stations (bottom).

Figure 3. A tagged crabeater seal being weighed prior to release. The image was taken aboard the R/V *Lawrence M. Gould* cruise in the winter of 2002.

ANIMAL TAGS AND TELEMETRY

Three of the US GLOBEC programs have included studies of top predators such as birds and marine mammals (California Current, Coastal Gulf of Alaska, and SO GLOBEC). Some of this work employed traditional ship-based survey methods, where the distribution of top predators was correlated with oceanographic features. This helped to develop an understanding of trophic relationships and the importance of biophysical forcing in their distribution in areas where oceanographic features such as currents, frontal systems, thermal layers, sea mounts, and continental shelf breaks increase the availability of prey (Costa et al. 2010). Advances in satellite telemetry, electronic tags, and remote-sensing methods have resulted in new tools that have allowed the movements and behavior of individual animals to be followed, which gives insights into the strategies employed by individual animals.

Animal Tags: Two types of tags were deployed on animals, those that record data and need to be recovered, and those that record and transmit data to shore-based stations via the ARGOS satellite. The satellite tags also provide an estimate of the animal's location, thus providing information on their movement patterns (Figure 3). A variety of sensors can be deployed on these tags that measure depth (pressure), water temperature, salinity, light level, and body temperature. An exciting recent development from observing diving predators, such as marine mammals, fish, and birds, has been the realization that electronic tag-bearing animals can be employed as autonomous ocean profilers to provide environmental observation data in diverse ocean regions (Costa et al. 2010; Figure 4). A significant advantage of tag-collected oceanographic data is that they are collected at a scale and resolution that matches the animals' behavior.

THE FUTURE

The instrumentation discussed in this article represents a very small subset of the newly advanced instruments that continue

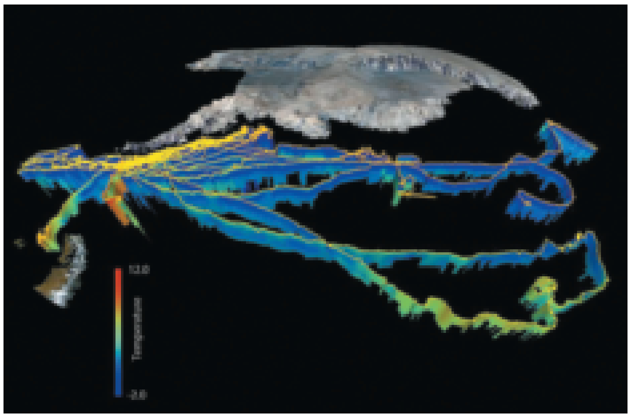

Figure 4. Curtain plots of temperature versus depth measured by tags on 12 different southern elephant seals that were tagged on Livingston Island and South Shetland Islands at the US Antarctic Marine Living Resources (AMLR) program's summer field camp during a 2007 deployment. The tracks represent about six months of data. The tracks extend from the Scotia Sea east of the Western Antarctic Peninsula and South America to the western end of the Amundsen Sea.

to be developed, often following closely on the heels of new fundamental, technological developments in fields other than oceanography. An increased understanding of ocean life forms will depend on the advances in instrumentation and will inevitably lead to an increased awareness of our dependence on them, and our need to wisely manage and protect this last frontier on the planet earth.

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PETER H. WIEBE, PH.D., received a B.S. degree in math and zoology in 1962 from Arizona State College in Flagstaff, Arizona and a Ph.D. degree in biological oceanography from the University of California, San Diego (SIO) in 1968. After a post-doctoral at the Hopkins Marine Station of Stanford University at Pacific Grove, California in 1968-69, he joined the scientific staff at the Woods Hole Oceanographic Institution, where he is now an Emeritus Senior Scientist in the Biology Department.

DANIEL P. COSTA (see bio on page 22)

ADDITIONAL READING

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ADDITIONAL RESOURCE

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

PHOTO CREDITS

Figure 1 (a): Courtesy of Cabell Davis, WHOI

Figure 2 (b): Courtesy of Phil Alatalo

Figure 2 (top): Courtesy of Austral Winter 2001

Figure 2 (bottom): Courtesy of Peter Wiebe

Figure 3: Courtesy of Dan Costa

Figure 4: Courtesy of [add if needed]

Data Management in US GLOBEC

By Peter H. Wiebe, Robert Groman, and Cyndy Chandler

Ocean science over the last half century has been transformed from *a predominately modular, single disciplinary and individualistic science into a national and multi-national interdisciplinary enterprise.*

This has been emphasized by Powell (2008): "Ocean science has long been interdisciplinary… Today, one can scarcely conceive of an oceanographic question that does not cut across disciplines"; and Briscoe (2008): "Ocean science must head toward more collaboration, because many of the research and applications questions we face demand teams of scientists and engineers (and probably social scientists and economists). Collaboration in the ocean sciences is critical to addressing emerging ocean problems, and is worth the effort." In addition, as noted by Powell (2008) and Briscoe (2008), multidisciplinary programs have been increasingly in the mainstream of oceanographic research and they have become more complicated with time.

The Global Ocean Ecosystem Dynamics Program (GLOBEC) was initiated in the early-1990s. There were three major efforts that took place in the Atlantic, Pacific, and Southern Oceans (Fogarty and Powell 2002). Just on Georges Bank and the surrounding area, there were 122 multidisciplinary cruises and considerable shore-based experimental work over the course of six years. Computer modeling studies and synthesis activities have been ongoing from the beginning to the present.

Accurate record keeping is fundamental to conducting excellent science, whether it is being done by a student doing an experiment in a high school setting, or scientists conducting cutting-edge research in their field. It begins at the start of a project before the first measurements are taken. It is not just the data, but the information about what the data are and when, where, and how the data were collected that is essential for single investigators and collaborative groups of investigators alike. Thus, data and information management was, from the start, an essential element in design, acquisition, and synthesis of datasets in the US GLOBEC program. Within the US GLOBEC program, a data management office and data repository were created, as the research activities on Georges Bank and the surrounding area began in 1994, and then were extended to serve the other modules conducting research in the Northeast Pacific and Southern Ocean. The office used open source software developed during an earlier multidisciplinary research program, the US Joint Global Ocean Flux Study (US JGOFS; Glover et al. 2006). Over the 17 years of serving US GLOBEC investigators, the software was modified and enhanced as the internet evolved. In 2006, the former US JGOFS and US GLOBEC data management offices were united to form the Biological and Chemical Oceanography Data Management Office (BCO-DMO; http://www.bco-dmo.org) with an expanded mandate to serve principal investigators funded by the NSF Biological and Chemical Oceanography Sections. The BCO-DMO manages a repository where marine biogeochemical and ecological data and information developed in the course of scientific research can easily be stored, protected, and disseminated on short and intermediate timeframes. The Data Management Office also strives to provide research scientists and others with the tools and systems necessary to work with marine biogeochemical and ecological data from heterogeneous sources with increased efficacy. The US GLOBEC program is now one of a number of programs whose data are being served by BCO-DMO, and the office manages data contributed from single investigator projects as well.

An important and distinguishing characteristic of the US GLOBEC and now the BCO-DMO approach is the provision of direct access to data, not just the metadata. The JGOFS/GLOBEC software is a very flexible, web-based system that easily serves both data and images. It is compatible with all standards-compliant browsers and it supports both distributed data servers and distributed clients through the use of standard web protocols. It provides a simple and relatively straightforward way to make ASCII data and images available on the web.

The BCO-DMO data management system is composed of three major components (Figure 1): the metadata database, the JGOFS/GLOBEC data management system, and the web interface supporting simple text-based and geospatial user interfaces that provide access to the information and data available from the BCO-DMO repository. The existence of sufficient metadata enables the discovery and accurate reuse of data by other researchers (and anyone else) beyond just the initial investigators who collect, analyze, process, and contribute the data. A MySQL-based relational database is used to store the metadata and other attributes deemed necessary to support discovery of and access to the stored data. The metadata database is used to generate human readable web pages of information and can supply the data dataset-specific information for compliance with metadata content standards, including Directory Interchange Format (DIF) records used

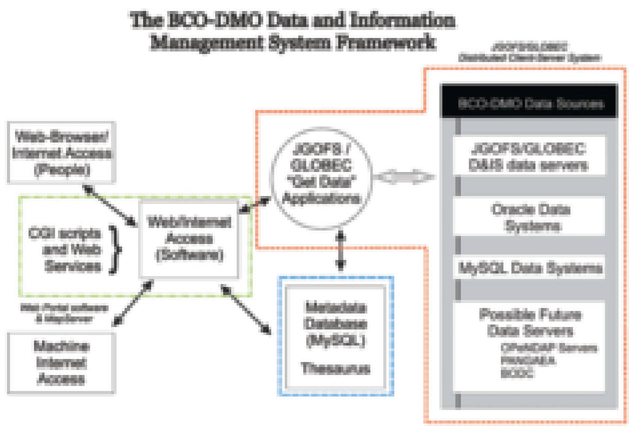

Figure 1. The image shows a drawing of the BCO-DMO data management system framework. (D&IS = Data and Information System; OPeNDAP = Open-source Project for a Network Data Access Protocol [http://www.opendap.org/]; PANGAEA = Publishing Network for Geoscientific & Environmental Data [http://www.pangaea.de/]; and BODC = British Oceanographic Data Centre [http://www.bodc.ac.uk/]).

by the Global Change Master Directory; Federal Geographic Data Committee (FGDC) Metadata Standard records; and international content standards such as ISO 19115 for "Geographic Information—Metadata."

One of the goals of BCO-DMO is to be able to display, synthesize, and share data when the data were collected by many different means, using many different instruments and labeled by different names. The metadata database contains specific information for each dataset, allowing investigators to use their own parameter names and descriptions to identify their measurements (e.g., temperature, Temp, T). These names are logically associated with terms defined in the BCO-DMO thesaurus of well-defined terms. Conversion utilities are being developed to resolve investigator supplied terminology in order to consistently serve data values from different sources. This process is not simple, as it entails not only resolving differences in units of measure, but also differences in instrumentation and acquisition and processing protocols. In the meantime, access is provided to the values in the units as supplied by the data contributors, and sufficient information is included to accurately describe the measured parameters.

web access to the data and metadata is provided in two modes: text-based and map-based. Text-based access uses the information contained in the metadata database to format displays of the available datasets, organized by the originating program, project, investigator name, instrumentation, parameter name, cruise, etc. As is common now, all web pages are generated from the most up-to-date information, on demand, and directly from the database. Links between pages enable one to locate related information and ultimately to be able to access and download the desired datasets. Map-based access uses the MapServer software, originally developed at the University of Minnesota, to provide geospatial access to the available datasets. In addition to being able to identify sampling locations on a map, several different data displays have been developed. These include X-Y plots, abundance plots, time-series plots, and 3D perspective ribbon plots, so that investigators can visualize data of potential interest and assess 'fitness for purpose' before deciding to download the data. Two popular exchange standards developed by the Open Geospatial Consortium, Web Mapping Service (WMS), and Web Feature Service (WFS) are supported, as well as the Keyhole Markup Language (KML) used by Google Earth and adopted as an OGC standard in 2008.

NEXT STEPS

As the GLOBEC program comes to a close, and the number of other contributing programs increases within the BCO-DMO repository, the issue of how an investigator gets access to a particular dataset of interest becomes a challenge. Semantic mediation is needed to make the BCO-DMO system internally interoperable and, in the longer term, interoperable with other repositories serving similar kinds of data in a way that is transparent to the user (scientist, manager, program manager, layman, etc). While BCO-DMO has the capability to acquire metadata and serve data from an individual PI, project, or program; and data from a number of programs are now being served, internal interoperability is not yet fully developed. The issue of getting access to a particular kind of data that resides in different data repositories is another important challenge, but one that is well-matched to an informatics approach. Research priorities include development of tools and interfaces to enable: more rapid and efficient data acquisition; enhanced data management; more effective data utilization and reuse; improved data visualization; and development of ontologies.

While there have been numerous and important technical advances since the beginning of the US GLOBEC program, there remain significant cultural impediments that are slowing our progress toward consistent, reliable open access to research data. Semantically enabled data system interfaces enhanced by the incorporation of advanced technologies will fall short of their potential, if research data are not made publicly available. There is still some resistance on the part of scientists and governments to making data freely available. Why? Reasons include: fear of lost opportunities; fear of negative repercussions due to misuse of data; lack of understanding about the requisite procedures; the investigator is not done publishing his/her papers based on the data; a graduate student is still analyzing the data; and the data are not yet final. In addition, there is a common perception that proper acknowledgment will not be given for data that are shared. However, there are real advantages to routine sharing of research data. A scientist's data are more valuable in the context of all the other datasets collected within a program, rather than individually. Additionally, each member of a collaborative project, who gains access to datasets contributed by others in the project, understands the requirement that all investigators contribute their data for use by others. The new recommendation described by Lowry et al. (2009) for assigning citable references to data published in public repositories, is one example of new approaches designed to ensure that researchers receive proper credit for making their data available for use by others.

EXPLORING THE GLOBEC DATA USING THE MAPSERVER

In the US GLOBEC program on Georges Bank, there were 31 broad-scale cruises to map the distribution and abundance of zooplankton and related environmental parameters such as temperature, salinity, chlorophyll, and nutrients. It is possible to get a first look at these data to see the cruise track, the locations of stations where measurements were made, and what measurements were made. To answer the question, "What was the distribution of the copepod (*Calanus finmarchicus*) in June 1999?" Here are the steps needed to get the answer.

1) Go to <http://www.bco-dmo.org/>.

2) Click on "Geospatial Access" in the left "Data Access" panel. A new page with the MapServer interface will appear.

3) On the top left side in the "Available Program(s)" scroll down to "U.S. GLOBEC (321)" and highlight entry by clicking on it. This will result in a smaller set of projects and deployments in the boxes to the right.

4) In the middle box where it says "Available Projects," click on "GB (151)." The resulting map display will focus in on all of the track-lines for cruises in the Georges Bank project. The cruise names will also appear in the "visible deployments" window.

5) In the "Available Deployments" scroll down to "AL9906" and click on it. This entry now will be the only one appearing in the "Visible deployments" window, and in the "map" window only the image of the cruise track will show.

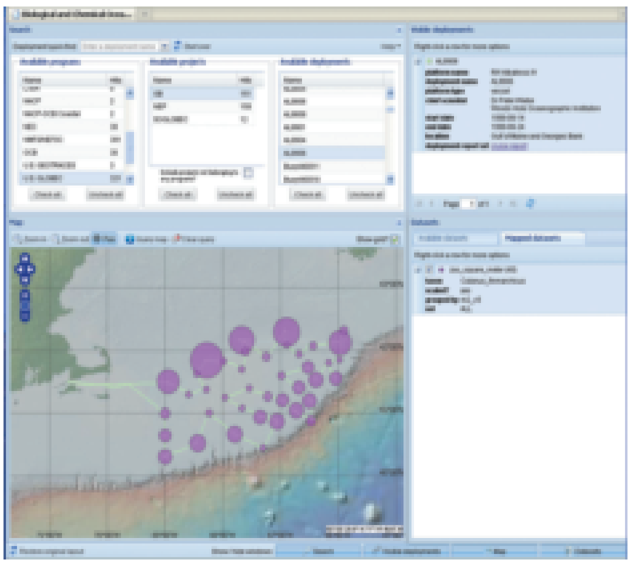

Figure 2. Plot of the distribution and abundance of the copepod (*Calanus finmarchicus*) on Georges Bank determined from counts of net tows taken on R/V *Albatross IV* cruise AL9906 in June 1999.

6) Click on the "+" to the left of "AL9906" to see information about this cruise.

7) Click on the colored square next to "AL9906." The cruise track-line will be highlighted and a list of datasets will be displayed in the "Datasets" window below.

8) In the "Datasets" window, click on the "+" next to the "zoo_square_meter" entry and another window "Mapping options for zoo_square_meter" will appear.

9) In the top pull-down scroll down to "*Calanus finmarchicus*" and highlight the entry by clicking on it and then click the "scale it?" check box.

10) Click on the down arrow next to the "group by..." select "m2_c5" (the fifth copepodid stage), and click on the down arrow next to the "Narrow by net" and select "ALL," and finally click on the "map_it" button.

11) A series of station locations where this species was found should be displayed on the image with circles scaled according to abundance (Figure 2). By running the mouse over a circle, the abundance of the species under a square meter of sea surface will appear.

To look at the vertical distribution of temperature at one of the stations on this cruise:

12) First uncheck the box used associated with the *Calanus finmarchicus* display (in the "Mapped datasets" window) to hide the distribution plot (in the "Mapped datasets" window). Then click on the "Available datasets" button.

13) Click on the "+" next to the "ctd_hydrography" dataset entry.

14) Click on "map-it." Stations should appear as colored dots on the cruise track.

15) Click on one of the dots and a pop-up box will appear.

16) Click on the "X" down arrow and select "temp."

17) Click on the "Y" down arrow and select "press."

18) Click on "graph_it." A plot of temperature versus pressure (depth) should appear in a separate window.

Have fun exploring the data and do not be afraid to download data to do more analyses and plots on your own computer. In the future this graphical data access tool will continue to be improved and the specific steps listed above may change. Updated instructions for this exercise will be maintained on the Supplemental Materials website for this issue (www.globec.org/publications/CURRENT).

CONCLUSION

Effective data management is predicated on the development of long-term collaborative partnerships between data management professionals and research investigators. The US GLOBEC and now the BCO-DMO collection of datasets contributed by researchers is a publicly available resource accessible via the BCO-DMO website. It supports synthesis and modeling activities, reuse of oceanographic data for new research endeavors, availability of "real data" for teachers/educators at K-12 and college levels to use in their classes, and provides decision-support field data for socially relevant issues.

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PETER H. WIEBE (see bio on page 29)

CYNDY CHANDLER is co-manager of the NSF funded Biological and Chemical Oceanography Data Management Office (BCO-DMO) and is an Information Systems Associate in the Marine Chemistry and Geochemistry Department at the Woods Hole Oceanographic Institution (WHOI). During her 30 years at WHOI, she has participated in 35 research cruises.

ROBERT C. GROMAN received a B.A. degree in physics in 1969 from Clark University in Worcester Massachusetts. He attended Dartmouth College in Hanover, New Hampshire as a graduate student in physics from 1969 through 1971. He earned a M.S. degree in Computer Science in 1981 from Worcester Polytechnic Institute in Worcester, Massachusetts. He joined the technical staff at the Woods Hole Oceanographic Institution in 1971, where is now an Information Systems Specialist.

GLOBEC Personality: From Planktoneer to Professor

By Jamie Pierson

My initiation into the GLOBEC program occurred on the January 1996

Broad-Scale survey cruise to Georges Bank. I was an undergraduate biology major and work-study employee in an oceanography lab, and I volunteered to go to sea at any available opportunity.

The research cruise was fraught with weather and equipment problems, and generated some spectacular (and real) sea-sickness stories, starring me as the protagonist; but I loved the work and the people I met. So much so, that for three- and a-half years after college I worked on the GLOBEC project, which included going to sea, sorting plankton, and managing the data (usually alongside many of the people I sailed with initially). That work experience taught me how science is really done, beginning with the ideas that lead to the proposals, through data collection and analysis, and culminating with the presentations and papers that communicate the results. I also learned which parts of science I enjoyed most and that oceanography is a truly interdisciplinary field that requires significant collaboration to be successful. I realized, too, that not all science jobs require a Ph.D.; however, if I wanted to be responsible for asking the big questions and leading the efforts to answer them, a doctorate degree was imperative.

Less than 15 years after that first cruise, I am an assistant research professor studying plankton ecology in coastal and oceanic ecosystems. My focus is on how individual behaviors and physiology affect the population dynamics observed in the field, a topic that piqued my interest when I first looked through a microscope at these animals during my work-study job. I still go to sea and am once again involved in GLOBEC; but instead of collecting data, I am now part of a team synthesizing what we learned and what it means in a changing environment.

PHOTO CREDIT

All Photos: Courtesy of J. Pierson

ACTIVITY: DRESS LIKE A PENGUIN

BY ANNIE THOMPKINS GUNTER AND DANIEL DICKERSON

THE FOLLOWING LESSON FOCUSES ON ADAPTATION, INSULATION, AND PENGUINS *and was developed to complement the science of the US Southern Ocean Global Ocean Ecosystem Dynamics (SO GLOBEC) program.*

The goal of the SO GLOBEC program was to understand the environmental and biological factors that influence the growth, reproduction, recruitment, and survival of Antarctic krill (*Euphausia superba*). Studies of the predators of Antarctic krill, such as penguins, seals, and whales, were integral to this goal.

FOCUS

Adaptation, insulation, penguins

GRADE LEVEL

5-8 (Life Science/Physical Science)

FOCUS QUESTION

How can penguins survive the extreme cold of the Antarctic?

LEARNING OBJECTIVES

- Students will be able to define structural adaptation and explain in general terms how this helps animals survive in extreme environments.
- Students will be able to explain insulation and identify insulating materials
- Students will be able to explain how penguins survive in cold environments and will be able to discuss how this might be affected by environmental change, such as a warming climate.

MATERIALS

- Containers (alike with openings large enough to add water and insert temperature probes/thermometers)
- Funnels (optional)
- Temperature probes/thermometers
- Shortening/petroleum jelly
- Hot water (measure the same amount for each group)
- Measuring cup with handle for hot water
- Wrapping materials (cotton, fur, wool, newspaper, aluminum foil, nylon, paper of different colors, etc.)
- Tape (duct, transparent, masking)
- Beaker/plastic box (large enough to place containers to prevent spillage)
- Paper
- Pencil

AUDIO/VISUAL MATERIALS

- Computer
- Projector
- Whiteboard/chalkboard

TEACHING TIME

Two 45-minute class periods, plus time for student research

SEATING ARRANGEMENT

Groups of four

MAXIMUM NUMBER OF STUDENTS

The maximum number of students is based on the amount of supplies available.

KEY WORDS

- Antarctic
- Penguins
- Anatomy
- Physiological adaptation
- Insulation
- Predator
- Warm-blooded
- Endothermic

BACKGROUND INFORMATION

Content: Penguins are warm-blooded animals (birds). The body temperature of a penguin is about 39°C (about 102°F) and must be maintained for survival. All animals get thermal energy from the food they eat. Internal and external structures such as fat skin and feathers allow them to maintain a balance between the heat produced and the heat lost. Animals usually choose an environmental temperature close to what can be maintain by their anatomical and physiological structures. The type of activity the animals engage in and shivering also help regulate heat production. Thermal insulation can be changed by increasing or decreasing blood supply and feather arrangement.

For background information about thermal insulation specifically for penguins, use the following website:
http://www.pinguins.info/Engels/Warmtebehoud_eng.html

The "Science of the Cold" website, which has a section on "How penguins survive cold conditions," provides useful general background information:
http://www.coolantarctica.com/Antarctica%20fact%20file/science/cold_penguins.htm

Additional general information on cold survival is given at the "Antarctic: 90 Degrees South" website:
http://westernreservepublicmedia.org/antarcti/insulat.htm

Pedagogy: The "Dress Like a Penguin" activity is an inquiry-based, technology-enhanced lesson designed to teach upper elementary/middle school students about how penguins can stand such a cold environment. Specifically, the lesson employs a 5-E Learning Cycle structure characterized by the following lesson components: Engage, Explore, Explain, Elaborate, and Evaluate (BSCS 2006). Additionally, the lesson incorporates instructional technologies (e.g., probeware). Where such technologies are not available, the low-technology equivalents may be used. However, the use of the low-technology equivalents is likely to require additional time to complete the activity and is often less accurate and precise.

LEARNING PROCEDURE

Engage

1. To prepare for this lesson you could do one or more of the following:

a) Show a clip from a penguin video/movie to get the students excited about the animals they are about to explore and ask them to describe some observations they made from the clip. Be sure that the video/movie does not provide explanations about penguins' insulation. At this point, we want the students to use their brains and start asking questions.

b) Have a non-graded pretest that may include questions about:

- How do penguins survive in extremely cold environments?
- What is insulation and how does it work?
- How might a warming climate impact penguins?
- What type of animal is a penguin?
- Are penguins warm- or cold-blooded?

Explore

1. Tell the students that in this investigation, "Dress Like a Penguin," the goal is to build a container that helps prevent heat loss. Explain that the materials selected and the final design must be agreed upon by the group. They can try any design they want as long it uses one or more of the materials in their kits.

2. Divide the class into groups based upon materials available and class size.

3. Distribute the kits of materials to each group.

4. Tell the students what each item in the kit is (you may want to ask how certain items are used in daily activities, but do not tell the students about any insulative properties).

5. Have each group brainstorm and illustrate its design on paper.

6. Using their drawings, have the students fashion their containers. **A time limit is suggested for design and construction, but be sure to allow for multiple trials and designs.**

7. Place completed design in a beaker large enough to prevent spillage.

8. Pour measured hot water in the opening of the container (teacher assisted).

9. Place the temperature probe/thermometer in the container and measure the temperature immediately. Record the temperature after obtaining a constant reading. The

thermometer should not touch the bottom/sides of the container.

10. After each one-minute interval (five-minute intervals if using alcohol thermometers), measure and record the temperature.

11. On a large piece of paper, have the students draw their design and list the materials used in their design on the top half of the paper. Then ask them to draw a graph showing their collected data on the bottom half of the same piece of paper. The papers can be placed around the room so everyone can see them.

Explain

1. Have each group make a presentation on its design and findings.

2. Ask the students to vote on which design was best at preventing heat loss.

3. Define insulation and use the students' designs as examples to illustrate your definition.

4. Explain to students or have them find explanations online about the following:

a) Penguins are birds and warm-blooded.

b) Penguins are insulated with a layer of fat and this helps them survive the cold.

c) Feathers are uniquely structured; cold climate penguins have longer feathers and thicker fat.

d) Colors absorb or reflect heat (refer to the penguins feathers being black and that this helps them survive the cold).

5. Briefly introduce the Southern Ocean GLOBEC program and how it helps us understand more about climate change. Talk about what warmer temperatures in the Antarctic could mean for an animal that is designed to stay warm.

Elaborate

1. Have each student draw a picture, and write one paragraph about a bird that they discovered while on an expedition to Antarctica. Tell the students that this bird has never been seen before, so they will need to describe it to the world because their camera was broken during their dangerous adventure. Tell them to be sure to use what they learned about surviving in the extremely cold Antarctic environment when thinking about their bird, because if it does not have certain characteristics people will question how it could survive and say that you are just suffering from "Cold Crazy."

2. Have students write a second paragraph describing how a warming climate would impact their bird and what they plan to do to help their bird's species survive.

3. Review these at home and re-teach as needed.

Evaluate

1. Once you feel confident the students can meet the objectives, provide an evaluation such as the following:

a) Have students write a brief essay describing why they should care about penguins and what might happen to penguins if the Antarctic gets warmer.

b) Have students list and describe the clothing and items they would include in a survival kit for the Antarctic cold and explain why.

THE BRIDGE CONNECTION

The following websites provide extensions of this activity:
http://expertvoices.nsdl.org/polar/2008/04/28/pierre-the-penguin-teaching-about-heat-and-insulation-through-adaptations/

http://westernreservepublicmedia.org/antarcti/howtouse.htm

http://www.pinguins.info/Engels/Warmtebehoud_eng.html

THE "ME" CONNECTION

Have students write a brief essay describing why they should care about penguins, and what might happen to penguins if the Antarctic gets warmer.

CONNECTIONS TO OTHER SUBJECTS

English/Language Arts, Mathematics

ASSESSMENT

Written reports and class discussions provide opportunities for assessment.

EXTENSIONS

Have students visit online and explore the different types of penguins.

Have students conduct the experiment, "Dress like a Penguin" using containers of the same shape but different sizes.

MULTIMEDIA LEARNING OBJECTS

Additional learning websites that are relevant to this activity are:
http://www.coolantarctica.com/Antarctica%20 fact%20file/science/cold_penguins.htm

http://www.pinguins.info/Engels/Warmtebehoud_ eng.html

OTHER RESOURCES

WHRO | The Public Telecommunications Center for Hampton Roads:
www.whro.org/

Nature episode, "***Penguins*** of the Antarctic":
http://www.pbs.org/wnet/nature/episodes/ penguins-of-the-antarctic/introduction/181/

Penguins resource:
http://www.seaworld.org/infobooks/penguins/home. html

NATIONAL SCIENCE EDUCATION STANDARDS

NS.5-8.1 SCIENCE AS INQUIRY
- Abilities necessary to do scientific inquiry
- Understanding about scientific inquiry

NS.5-8.2 PHYSICAL SCIENCE
- Transfer of energy

NS.5-8.3 LIFE SCIENCE
- Structure and function in living systems
- Regulation and behavior
- Populations and ecosystems
- Diversity and adaptations of organisms

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ANNIE THOMPKINS GUNTER is a part-time STEM instructor at STARBASE Victory, Portsmouth Public Schools, Portsmouth, Virginia. After 35 years of teaching middle school and high school sciences, she retired from Portsmouth Public Schools in 2004. During her teaching career, she also served as Mathematics, Science, and Technology Magnet School facilitator and science department chairperson, also in Portsmouth Public Schools.

DANIEL DICKERSON, PH.D., is Associate Professor of Science Education in the Department of STEM Education and Professional Studies at Old Dominion University. His research focuses on the teaching and learning of earth and environmental science content, environmental education, and socioscientific issues in science education. He is a former high school earth science teacher who has served as an Investigator or Evaluator on NOAA, NSF, US Department of Education, Institute of Museum and Library Services (IMLS), and state- and foundation-funded projects.

PHOTO CREDIT

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Epilogue

By Elizabeth Turner and Cynthia Suchman

THIS ISSUE OF *CURRENT* WAS CONCEIVED AS A MEANS TO INFORM THE MARINE *education community about scientific discoveries, technological developments, and data publicly available through the US GLOBEC program. We hope it will help to expand the use of GLOBEC science in educational activities.*

In addition, we want to highlight specific educational accomplishments of the program: taking teachers to sea, training graduate students in cross-disciplinary research, and online access to scientific results.

The US GLOBEC program has been jointly supported and managed by the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA). The agency partnership was formed to support interdisciplinary research to enhance our understanding of how marine ecosystems operate in relation to changing environments. Each of the Federal sponsors has broad goals related to education and outreach designed to meet national needs. Broad dissemination of scientific findings and the training of a future workforce that can meet tomorrow's environmental challenges are important goals for both agencies.

One mode of engaging educators occurred during the course of the field program in the Northeast Pacific program. Mr. John Hercher, a science teacher at South Salem (Oregon) High School, was able to join a US GLOBEC research cruise in the northern California Current through the NOAA Teacher at Sea program. He lived with the scientific crew for three weeks at sea and posted daily updates (http://globec.oce.orst.edu/outreach/tas/index.html). Subsequently, he developed a classroom exercise on comparing measurement scales of ocean temperatures, available at http://globec.oce.orst.edu/outreach/tas/classroom.html.

A primary contribution of US GLOBEC to education has been through the support of graduate students. Students supported under GLOBEC investigators had experience with a large sea-going field program and the use of the large data sets collected. Students also were exposed to a large number of collaborators at different institutions. Because the program was sustained over such a long period of time, a number of young scientists matured during its tenure and now hold faculty positions. In these positions they are training in working as part of a large research program, shaping how they approach their own science.

In addition to the myriad students supported under individual NSF or NOAA awards, GLOBEC has sponsored training activities to give students an indepth understanding of models and analysis methods for studying climate effects on marine ecosystems, and encourage them to pursue further applications of techniques developed through the GLOBEC program (see http://www.cgd.ucar.edu/events/marine/event.details.html). US GLOBEC has also disseminated project results through a seminar series, with archived presentations available online at

http://usglobec.org/NOAA_seminars/. These presentations have formed the basis of graduate-level seminar courses, and continue to provide access to the scientific findings in a format more accessible to the public and policymakers than a scientific paper published in a professional journal.

The approach and discoveries of the US GLOBEC program have had an enormous impact on the ocean science community. US GLOBEC scientists were instrumental in making new discoveries (e.g., unexpected hypoxia in Oregon described by Barth in this issue). In some cases, US GLOBEC provided the first measurements ever made in particular geographic areas for certain seasons (i.e., winter ocean current patterns in the Southern Ocean). Data collected by US GLOBEC provided new insights into the mechanisms that drive marine population dynamics. Program results also point out the fact that hypotheses that were put forth at the beginning of the program may not be supported by the research findings (see the article by Bond in this issue regarding co-variability of salmon populations in the Gulf of Alaska). This is an important and under-appreciated aspect of how science works.

As a large coordinated program, with scientists at sea for long periods, GLOBEC also became an example of how the community of ocean scientists functions, interacts, and evolves. The program recognized the need for collaboration across disciplines to address complex problems, and led the development and better use of emerging technologies to sample physics and biology in new ways (see Weibe and Costa, this issue). Modeling systems were developed to integrate research findings from physical and ecological fields (see Haidvogel and Curchitser, this issue), and we now have visualization approaches to display and communicate model results to diverse audiences. The integration of disciplines has been a hallmark of the program, and one of its lasting legacies is to serve as an example of collaboration toward a common purpose.

Finally, US GLOBEC represents a multi-year investment in a continuing research program. Because the questions asked and the regions studied were large-scale both in terms of time and space, it was necessary to have a long view in planning and carrying out the research. Many stories of science focus on the "Eureka" moment, but neglect to point out the long history of work that leads up to it. The agency sponsors are proud of being able to support US GLOBEC over the long term, and celebrate the program's accomplishments. We expect that the impact of the program will continue through the sampling methods devised, the data collected, the model techniques improved, and the graduate students trained.

BETH TURNER, PH.D., is an oceanographer and senior program manager at the Center for Sponsored Coastal Ocean Research in the NOAA National Centers for Coastal Ocean Science. In addition to managing other coastal research programs, she has served as the US GLOBEC program manager since 1998. Prior to joining NOAA, Beth spent two years as a program officer in the Biological and Chemical Oceanography program at the US Navy's Office of Naval Research. She was also a study director at the National Academy of Sciences Ocean Studies Board. Beth holds a Ph.D. in Biological Oceanography from the University of Delaware, a M.S. in Marine Environmental Science from SUNY Stony Brook, and a B.A. in Biology from Texas Christian University, and completed post-doctoral work at Rutgers University and the University of Maryland at College Park.

CYNTHIA SUCHMAN, PH.D., is an associate program manager in the Biological Oceanography Program of the National Science Foundation (NSF). In addition to oversight of the US GLOBEC program during her tenure at NSF, she participated in US GLOBEC field programs as a graduate student at the University of Rhode Island and a post-doctoral scientist with the NOAA Northwest Fisheries Science Center. Later this year, Dr. Suchman will become the Executive Director of the North Pacific Research Board.

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