EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 91 NUMBER 48

30 NOVEMBER 2010

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How Does Climate Change Affect the Bering Sea Ecosystem?

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The Bering Sea is one of the most productive marine ecosystems in the world, sustaining nearly half of U.S. annual commercial fish catches and providing food and cultural value to thousands of coastal and island residents. Fish and crab are abundant in the Bering Sea; whales, seals, and seabirds migrate there every year.

In winter, the topography, latitude, atmosphere, and ocean circulation combine to produce a sea ice advance in the Bering Sea unmatched elsewhere in the Northern Hemisphere, and in spring the retreating ice; longer daylight hours; and nutrient-rich, deep-ocean waters forced up onto the broad continental shelf result in intense marine productivity (Figure 1). This seasonal ice cover is a major driver of Bering Sea ecology, making this ecosystem particularly sensitive to changes in climate. Predicted changes in ice cover in the coming decades have intensified concern about the future of this economically and culturally important region. In response, the North Pacific Research Board (NPRB) and the U.S. National Science Foundation (NSF) entered into a partnership in 2007 to support the Bering Sea Project, a comprehensive $52 million investigation to understand how climate change is affecting the Bering Sea ecosystem, ranging from lower trophic levels (e.g., plankton) to fish, seabirds, marine mammals, and, ultimately, humans. The project integrates two research programs, the NSF Bering Ecosystem Study (BEST) and the NPRB Bering Sea Integrated Ecosystem Research Program (BSIERP), with substantial in-kind contributions from the U.S. National Oceanic and Atmospheric Administration (NOAA) and the U.S. Fish and Wildlife Service.

This 6-year study of the Bering Sea ecosystem links nearly a hundred principal scientists through an integrated program of field sampling, process, and modeling studies. The program's goal is to define the mechanisms that create and sustain this highly productive ecosystem and to understand how those mechanisms may be altered as climate changes. Bering Sea Project participants finished their field work in October 2010 and are now focusing on data analyses and syntheses across project components. To date, four key messages have emerged from the data collected during the 2007–2010 field years.

Northern Bering Sea Will Remain Cold and Dark

While the cross-shelf structure on the eastern Bering Sea shelf is well documented, the north-south structure had been poorly understood. Before this program, it was hypothesized that regional warming would result in significant warming of northern Bering Sea shelf waters. But Bering Sea Project scientists have found that the north-south structure is strongly modified by a combination of cross-shelf advection and tides and that the northern shelf with its limited sunlight and proximity to land will continue to have extensive ice cover during winter and especially in the spring, thus maintaining cold bottom waters throughout the year. The consequences for major food webs and commercial fishing interests are substantial, with a cold northern ocean limiting northward movement of subarctic species such as pollock and cod.

Cycles of Carbon and Nutrients: Strong in Late Spring and Summer

A key research theme for the Bering Sea Project is to understand how changing climate conditions and seasonal ice coverage affect production. A pattern has emerged from fieldwork results: With ice retreat in spring, nutrients rapidly become depleted as phytoplankton growth rates and primary production increase. A large fraction (75%) of primary production in shallow ice-covered areas falls to the seafloor, providing energy to benthic organisms (e.g., clams), with relatively little being grazed by zooplankton, fish, or other planktivores. By contrast, in ice-free waters, zooplankton graze nearly half of primary production. During summer, large krill graze only a small fraction of primary production, yet microzooplankton grazing sharply reduced overall export to the benthos. Taken together, results show that greater amounts

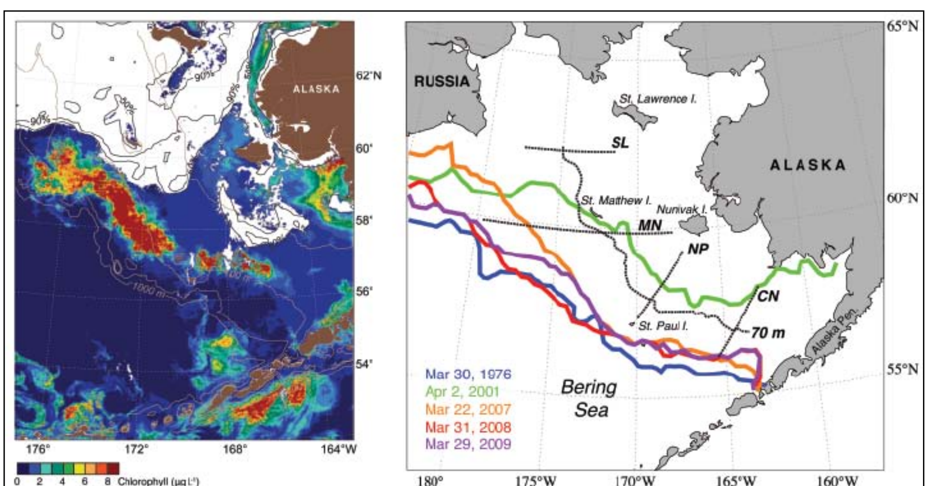

Fig. 1. (left) A composite chlorophyll image from 2–4 May 2009 that demonstrates the extensive phytoplankton bloom at the retreating ice edge, typical of the southeastern Bering Sea shelf in spring. The white area is sea ice, with contours of 50% and 90% ice coverage indicated. (right) Maximum sea ice extent and date for the three core study years and for the years of greatest (1976) and least (2001) ice extent over 1972–2010, the period for which good ice data are available. Principal cross-shelf sampling lines and the 70-meter isobath sampling line are shown (dotted lines). Each cross-shelf line is labeled with two letters that represent identifying geographic features. Each cross-shelf line intersects one of four biophysical moorings located along the 70-meter isobath.

of carbon and nutrients were recycled in the water column than expected for such a productive ecosystem.

Prewinter Energy Reserves: Critical for Overwinter Survival of Young Pollock

Walleye pollock, a cod-like species, dominates pelagic fish biomass in the southern Bering Sea and is the largest single-species fishery in the United States—in 2008 the wholesale value of this fishery was $1.4 billion. Recent catches have decreased and recruitment was poor during the relatively warm years of 2001–2005, generating interest in climate-related ecosystem linkages.

The Bering Sea Project is investigating those climate linkages. For example, during the warm years of 2001–2005, newly hatched pollock were abundant in summer and fall but were found to have low energy reserves, perhaps due to the almost complete absence of their main zooplankton prey. High overwintering mortality resulted in few first-year pollock being found the following spring. In contrast, overwinter survival of juvenile pollock during the recent cool years of 2006 and 2008 was high. Current Bering Sea Project work focuses on elucidating mechanisms driving these climate-related differences.

Reproductive Success Tied to Seabird Foraging Trip Length

Another key Bering Sea Project research theme is how predators are affected by climate-forced changes in the distribution of prey. Historical information suggests that Pribilof Islands kittiwakes and murres (piscivorous seabird species) forage in a relatively even distribution and consume juvenile pollock as their primary prey. During 2007–2009, Global Positioning System data from tagged birds and at-sea surveys revealed that thick-billed murres were distributed along the outer domain of the eastern Bering Sea shelf; areas of concentration were consistent from year to year. In contrast, black-legged kittiwake concentrations shifted over large distances (hundreds of kilometers). At colonies where foraging trips were longer, reproductive success was lower, presumably because foraging costs were higher and chicks were fed less often. This trip length effect was also found for northern fur seals; pup weights were lower at the one of two rookeries studied with longer trip lengths.

Next Steps

The Bering Sea Project provides the most comprehensive investigation of the Bering Sea ecosystem to date and includes local and traditional knowledge investigations that will bring native understanding of the ecosystem together with other research. Ecosystem modeling will link the entire project in an attempt to predict the impacts of climatic change on the Bering Sea ecosystem. As of October 2010, the Bering Sea Project has completed its four field years and is transitioning to data analysis and synthesis. Interested readers are encouraged to visit the project Web site to learn more (http://bsierp.nprb.org).

Acknowledgments

The Bering Sea Project and this brief report arise from the collective efforts of a tremendous group of principal investigators, students, field and vessel crews, and technicians.

—Michael F. Sigler, Alaska Fisheries Science Center, NOAA, Juneau; H. Rodger Harvey, Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons; Carin J. Ashjian, Woods Hole Oceanographic Institution, Woods Hole, Mass.; Michael W. Lomas, Bermuda Institute of Ocean Sciences, St. George's, Bermuda; Jeffrey M. Napp, Alaska Fisheries Science Center, NOAA, Seattle, Wash.; Phyllis J. Stabeno, Pacific Marine Environmental Laboratory, NOAA, Seattle, Wash.; and Thomas I. Van Pelt, North Pacific Research Board, Anchorage, Alaska; E-mail: tvanpelt@nprb.org

Expanding Carbon Data Collection From the Ocean's Interior

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Through global climate studies and atmospheric surveys, scientists now know that the release of carbon dioxide (CO_2) into the atmosphere by burning fossil fuels has the potential to alter global climate. The oceans represent a key sink for anthropogenic CO_2 (C_{ant}), but their capacity as a sink and how this sink has evolved over time have yet to be fully determined. Further, uptake of CO_2 from the atmosphere directly influences the world's oceans by, for instance, increasing acidity, but how future changes will evolve is also poorly known.

The reason little is known about oceanic C_{ant} is because only a small percentage of the ocean has been tracked by research cruises that collect carbon data. Even data from those cruises lack the standardization needed to compare different results over time. To help fix this, a collection of interior ocean carbon data has recently been published: The Carbon Dioxide in the Atlantic Ocean (CARINA) data collection contains information from 188 oceanographic cruises and represents a major boost of readily available, high-quality, and uniform data. A companion effort, the Pacific Ocean Interior Carbon (PACIFICA) data collection, will increase global coverage by providing standardized products from the Pacific Ocean. Combined, CARINA and PACIFICA will help to boost future iterations of the Global Ocean Data Analysis Project (GLODAP; see Figure 1).

Structure of CARINA

CARINA consists of two parts: the individual cruise files with the measured data converted to common units and accompanied by metadata and appropriate references, and a set of three regional, internally consistent data products. These regional data products cover the Atlantic Ocean (the area between the Greenland-Scotland Ridge and about 30°S), including data from 98 cruises; the Arctic Mediterranean Sea region (the area north of the Greenland-Scotland Ridge and Bering Strait, encompassing the Arctic Ocean and the Nordic seas), including data from 62 cruises; and the Southern Ocean (the ocean south of about 30°S), including data from 37 cruises.

CARINA started about a decade ago as an informal project with limited funding and by 2004 had accumulated data from approximately 30 North Atlantic cruises. In 2005 it was revived with funding from the European Union project CARBOOCEAN and evolved into a consistent set of carbon-relevant data from the Atlantic, Arctic, and Southern oceans. Details of the procedures and calibration results have been published in a special issue of *Earth System Science Data* (*ESSD*) (see, e.g., *Key et al.* [2010] and http://www.earth-syst-sci-data.net/special_issue2.html), and the body of data collected is available from the Carbon Dioxide Information Analysis Center (CDIAC; http://cdiac.ornl.gov/oceans/CARINA/).

A Broad Effort to Understand Interior Ocean Carbon

Until about a decade ago one of the largest uncertainties in global climate change studies was the inventory of C_{ant} stored in the ocean. Several studies at that time reported on regional inventories of C_{ant} in the ocean, but a robust data-based global estimate was not available mainly because of the absence of a high-quality uniform data set. As a direct response to this, GLODAP was created by a team of mainly U.S. scientists, producing a global, internally consistent set of ocean carbon data from nearly 100 ocean research cruises that were available at that time [e.g., *Key et al.,* 2004]. The GLODAP data have been widely used for biogeochemical and physical investigations for both modeling and data analysis. For instance, *Sabine et al.* [2004] produced the first data-based global ocean C_{ant} ocean inventory. Although global in extent, GLODAP had only very sparse data coverage in the North Atlantic in relation to the concentration gradients and complex circulation found there and almost no data north of about 60°N. CARINA