BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Demography and Population Dynamics of Bering Sea Krill

COMPLICATED LIFE HISTORIES ACROSS THREE OCEANOGRAPHIC DOMAINS

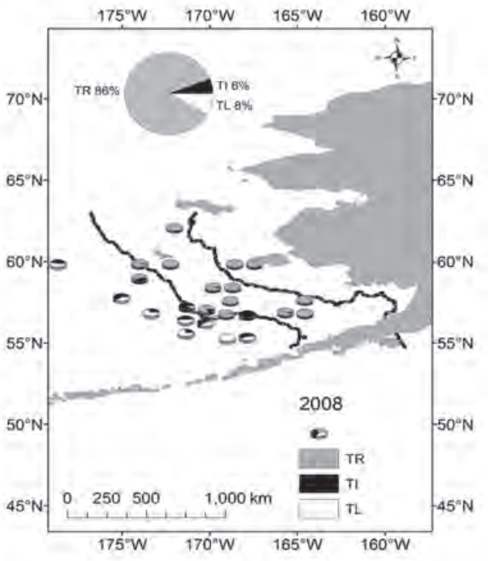
Krill are an important food source for many larger animals such as whales, seals, and fish. As for many other organism populations, krill populations and their demographic structure in the ocean are due to their growth and death rates. Under favorable conditions the krill grow fast and build up their lipid storage for use during unfavorable conditions, such as the dark cold winters of the Bering Sea. In unfavorable conditions, krill populations have decreased growth rates and may even shrink. Krill growth and survival are structured, in part, by food availability. Important questions of intrinsic interest arise: How are growth and death rates affected by the changing conditions in the Bering Sea? How do these changes in growth and death relate to the demographic structure of krill?

In the Bering Sea, three major euphausiid groups occupy different habitats. *Thysanoessa raschii* were found in abundance in the middle and inner domains. *T. inermis* occurred more abundantly in the outer domain and *T. longipes* were more abundant through the outer domain and beyond the shelf-break (Fig. 1).

The demographic structure varied among different krill species. In general, the dominant age peaks for *T. raschii* and *T. inermis* were in the 3-9 month range. But in spring 2009, older individuals tended to be more abundant for both krill species (Figs. 2, 3).

continued on page 2

Fig. 1



Spatial distribution of different krill species: T. raschii *(TR),* T. inermis *(TI), and* T. longipes *(TL) in 2008. Two black lines indicate 50 m and 100 m bathymetry, respectively.*

The Big Picture

The Bering Sea is a very productive ecosystem, with many economically important organisms that rely on krill as a prey item. Variability in krill growth and survival is structured as a climate-driven bottom-up control system of food availability and predation. This project examines growth and vital rates in krill species to better understand their population dynamics and their trophic linkage with predators. Three key questions are: (1) How does krill demographic structure (age and size) vary across three oceanographic domains in the Bering Sea: the inner, middle, and outer shelf? (2) How do growth and vital rates vary in the three domains? (3) How do the variations in growth and vital rates contribute to different demographic structures? During the Bering Sea Project field years 2007 – 2010, several key parameters of krill populations were measured (age, lipid content, and growth) from the same individuals, which provided unprecedented detail for modeling vital rates. We developed an individual-based model to simulate demographic structure, and we concluded that depending on the location (e.g., inner shelf versus outer shelf), krill growth and survival respond differently to large-scale oceanographic changes.

INTEGRATION AND MODELING OF SPATIAL-TEMPORAL VARIATION IN VITAL RATES FOR EUPHAUSIIDS IN EASTERN BERING SEA: IMPLICATIONS FOR DEMOGRAPHICS
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

The growth of *T. inemis* and *T. raschii* tended to be faster in 2008 than in 2009, whereas the growth of *T. rashii* was similar in 2008 and 2009. The difference in growth could be explained by age structure and survival rates: more young individuals, faster growth rate for the population; higher survival rate for old individuals, slower growth rate for the population.

How We Did It

At sea, we deployed a Multiple Opening and Closing Net with an Environmental Sensing System (MOCNESS) to collect krill samples. Samples were preserved and sorted to species level in the lab. Live krill samples were also collected at sea and then frozen for later age determination. A biochemical approach was used to determine krill ages in the lab. To examine the relationship between growth, survival, and demographic structure, individual based models were fit to the observed demographic and size data in spring and summer to determine krill growth rate estimates for 2008 and 2009.

Why We Did It

Krill are important prey for many predators, such as pollock, whales, seabirds. Their abundance will have major impacts on the food web. Due to their complicated life history and multiple molting cycles, it is difficult to determine their demographic structure and estimate their growth using conventional methods. Information on demographic structure, growth, and survival will facilitate our understanding of krill's response to environmental changes, which in turn will improve prediction of the health of the predator populations.

Hongsheng Bi, University of Maryland Center for Environmental Science

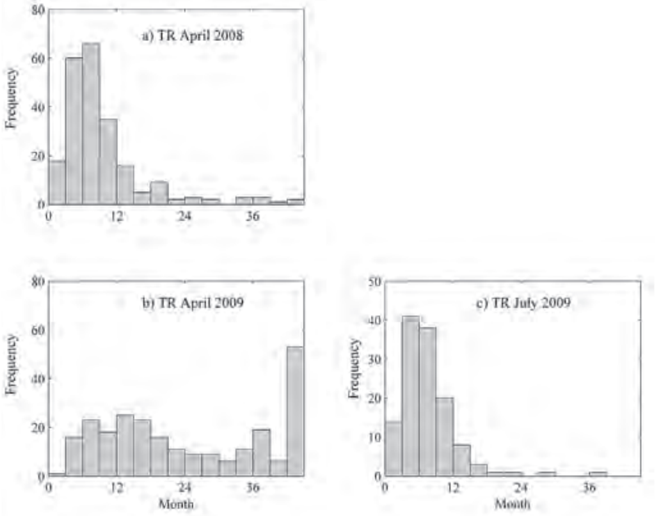
Alexei Pinchuk, University of Alaska

Rodger Harvey, Old Dominion University

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

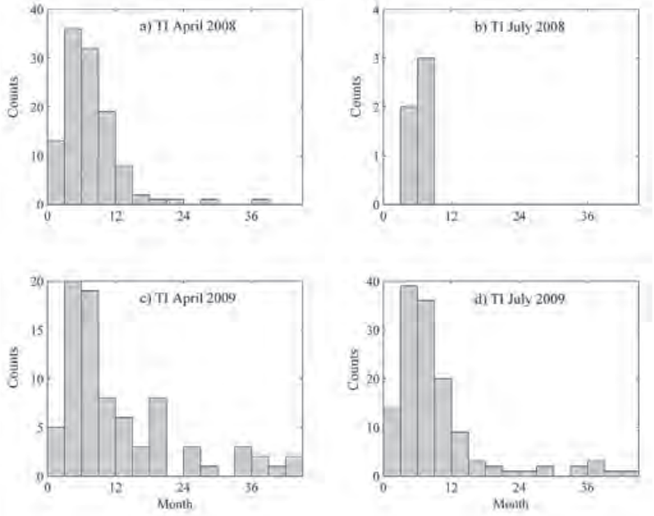
Deployment of a Bongo net to collect krill.

Fig. 2



Spring and summer age structure for T. raschii *in 2008 and 2009. In spring 2008, 6-9 month old krill were common. In spring 2009, older krill were more abundant, but disappeared in summer. No data were available for* T. raschii *in summer 2008.*

Fig. 3



Spring and summer age structure for T. inermis *in 2008 and 2009. Note that older krill were more abundant in spring 2009.*

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

What is the Crystal Ball Saying about the Bering Sea?

NOTHING, BUT CLIMATE MODELS ARE CALLING FOR VARYING AMOUNTS OF WARMING

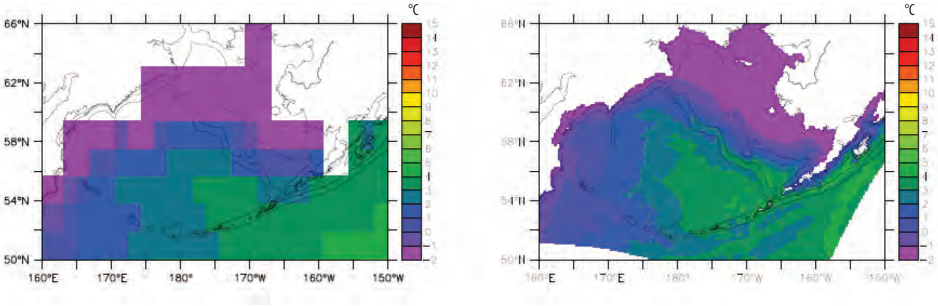
It is a safe bet that the future will include a warmer Bering Sea. But it is uncertain exactly how climate change will be manifested, and in particular, how fast it will warm in summer versus winter, and in the north versus the south. Nevertheless, these details in the climate forcing are key in terms of their impacts on plankton community structure and distributions and, ultimately, the entire marine ecosystem. We addressed the formidable problem of how climate change is liable to impact lower-trophic levels, i.e., the base of the food web, using groundbreaking methods and massive computing resources.

How We Did It

Our approach featured high-resolution ocean model simulations using the Regional Ocean Modeling System (ROMS). This model includes interactions among physical water properties, nutrient concentrations, and the growth and consumption of groups of plankton crucial to fish, sea birds and marine mammals. The regional simulations were embedded in large-scale atmospheric and oceanic conditions from global climate model predictions. ROMS is much more realistic than the global models in representing smaller-scale effects of bottom topography on the currents and temperature (Figure 1).

continued on page 2

Fig. 1



Surface temperatures for the present climate during February from the Canadian Centre for Climate Modeling and Analysis (CCCMA) global climate model (left panel) and from ROMS (right panel) using the CCCMA for the large-scale atmospheric and oceanic forcing.

Sandra Parker-Stetter

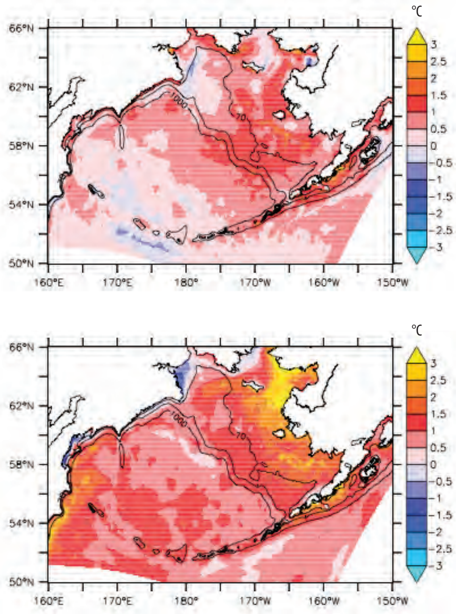
Euphausiids, also known as "krill."

The Big Picture

While global climate models provide consistent global-scale predictions over the next few decades, they differ significantly in their predictions on regional scales. By using an ensemble of such models to drive a coupled physical-ecosystem model for the Bering Sea region, we were able to achieve consistent estimates of how the euphausiid population, an important food source for commercial fish species, would change on those same time scales.

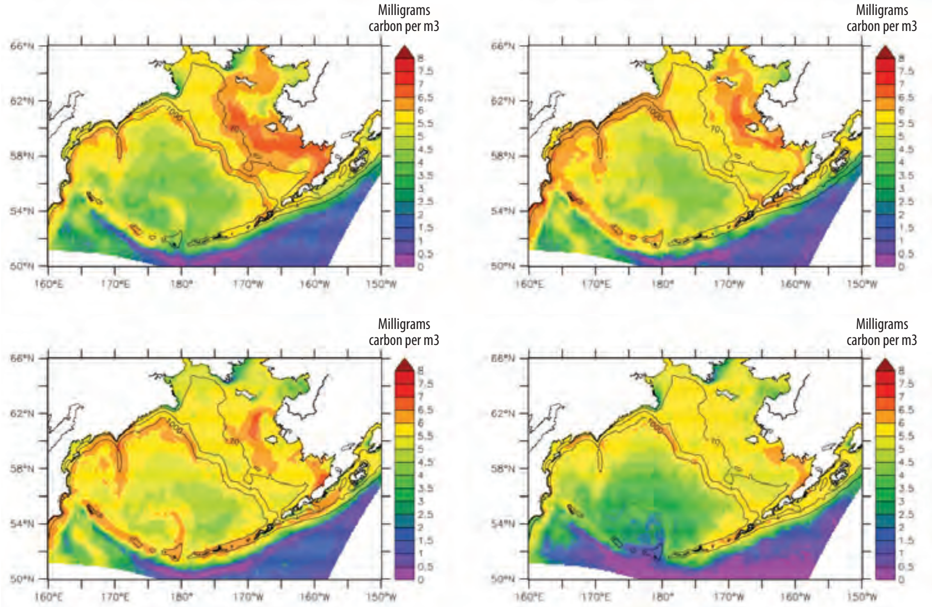
DOWNSCALING GLOBAL PROJECTIONS TO THE ECOSYSTEMS OF THE BERING SEA WITH NESTED BIOPHYSICAL MODELS
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

Fig. 2



Surface temperature changes for August from the present climate to the 2030s from ROMS using the CCCMA (top panel) and Model for Interdisciplinary Research on Climate (MIROC) (bottom panel) global models for the climate forcing.

Fig. 3



Near surface concentrations of euphausiids in August from ROMS projections using the present climate forcing (upper left panel), and from ROMS using the climate forcing of the 2030s from the CCCMA climate model (upper right), ECHOG climate model (lower left) and MIROC climate model (lower right).

The climate model forecasts that have been carried out are mostly similar in terms of their projections of global means, but they predict different future climates from a regional perspective (Figure 2). There is little justification for selecting one of these models over others to specify the large-scale future climate forcing of the Bering Sea. It is therefore prudent to take a multiple-model approach, and focus on the range of probable outcomes.

An illustration of this range is provided by a set of ROMS projections of euphausiid distributions in August (Figure 3). Euphausiids represent key prey for a number of species, including young walleye pollock. There is consensus from the ROMS model projections that euphausiid populations are likely to decline on the eastern Bering Sea shelf. On the other hand, there is conflicting evidence from the model with respect to the sense of the expected changes in euphausiid populations over the deep basin of the Bering Sea.

Why We Did It

Our project represented an ambitious effort, and we have learned a lot along the way about the crucial interactions and choke-points in the physical forcing of the Bering Sea ecosystem. While we may not be able to assert exactly how climate change will play out in the region, our research provides insights for effective monitoring of this system and towards the development of improved forecast models.

Nick Bond, University of Washington/JISAO
Georgina Gibson, University of Alaska Fairbanks
Al Hermann, University of Washington/JISAO

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

The Spring Bloom Matters

THE IMPORTANCE OF THE SPRING BLOOM TO THE OVERALL PRODUCTIVITY OF THE BERING SEA

The success of the highly productive Bering Sea fishery depends on massive blooms of tiny, single-celled plants that occur each spring when increasing light and abundant nutrients enable these plants to flourish both in the ice (ice algae) and in the water column (phytoplankton) as the sea ice retreats. These blooms support a zooplankton community that has just awoken from a period of rest during the long, dark, cold winter. This community is made up of the small, unicellular microzooplankton and the larger, multicellular, mostly crustacean mesozooplankton dominated by copepods and krill. The zooplankton community, in response to the spring bloom, dramatically increases its numbers and biomass and provides an abundant, highly nutritious food source for seabirds, mammals and fish. This project seeks to better understand the importance of the spring bloom to the Bering Sea ecosystem and to predict how these blooms might be altered for better or worse in a warmer Bering Sea.

What We Did

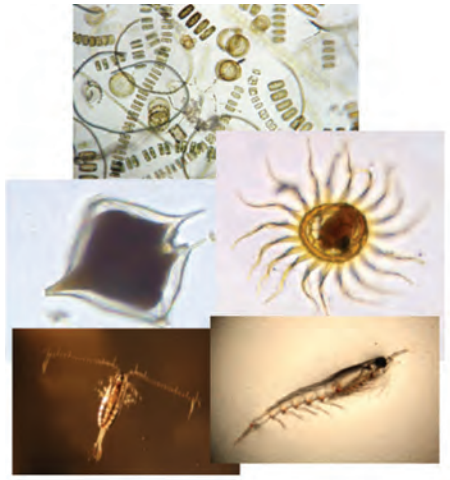
We collected samples over a large region of the shelf, using ice cores, water samplers and nets to identify and quantify the biomass of the planktonic ecosystem components. Shipboard experiments measured important biological rates, such as zooplankton feeding, growth and reproductive rates. Datasets then were integrated and synthesized to determine regional patterns and year-to-year variability in the biomass, productivity and consumption rates of different planktonic components. A new planktonic ecosystem model was developed to better understand the food web dynamics and to predict the response of the planktonic ecosystem to future climate changes.

What We Found

We found the spring ice-associated bloom (Figure 1) to be of vital importance to the productivity of the Bering Sea. It begins the plankton growing-season and supplies a large and dependable food source to which the life cycles of many of the important zooplankton, and

continued on page 2

Fig. 1



The Bering Sea planktonic food web in spring (not to scale). (Top) A mixed diatom assemblage from the Bering Sea spring bloom. Diatoms are the dominant component of both ice algal and phytoplankton communities during spring. Photo credit: E. Sherr. (Middle) Dinoflagellates like this Protoperidinium *sp (left) and ciliates similar to the* Leegardiella *sp. (right) are important members of the microzooplankton communities. Photo credit: E. Sherr. (Bottom) The copepod* Calanus glacialis/marshallae *(left) and the euphausiid (krill)* Thysanoessa raschii *(right) are dominant components of the mesozooplankton. Photo credit: C. Gelfman.*

The Big Picture

Using a modeling approach combined with extensive data collection and at-sea experiments, we tackled a conundrum: why do years with warm ocean temperatures result in low overall success of copepods and other large zooplankton, despite better food supplies and faster growth? Copepod overall success is extremely sensitive to winter prey concentrations, even though those concentrations are orders of magnitude lower than those during the spring bloom. Increased mortality during warm years and/or lower growth rates at warm temperatures that exceed the optimal thermal tolerance for the animals also are important. Our model provides almost as many new questions as answers, and can be used to guide future research directions.

LINKING SEA-ICE RETREAT TO PLANKTON COMMUNITY STRUCTURE AND FUNCTION IN THE BERING SEA: DATA SYNTHESIS, BIOPHYSICAL MODELING, AND MULTI-DECADAL PROJECTION
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

benthic, species are timed.

The planktonic food web in the Bering Sea is far more complex than simply large zooplankton feeding on large phytoplankton. Copepods and krill all readily feed on ice algae, phytoplankton and microzooplankton. Frequently microzooplankton, not phytoplankton, are their preferred food.

The life cycles of many important zooplankton species are timed to take advantage of the spring bloom. Peak reproduction of the large copepod *Calanus glacialis/marshallae* coincides with the bloom. Adult females that have survived the food-limited winter are mature and ready to take advantage of the rich bloom food environment. These animals respond rapidly to the increased food supply by producing up to 50 eggs per female per day. The eggs and early developmental stages of copepods are an important food source for larval fish.

The spring bloom provides an almost inexhaustible food supply allowing copepods to increase their biomass by up to 10-fold between early spring and summer. Even so, the zooplankton community leaves much of the spring bloom production un-grazed. This excess productivity falls to the sea floor where it supports a rich benthic community including commercially important crustaceans such as king crab.

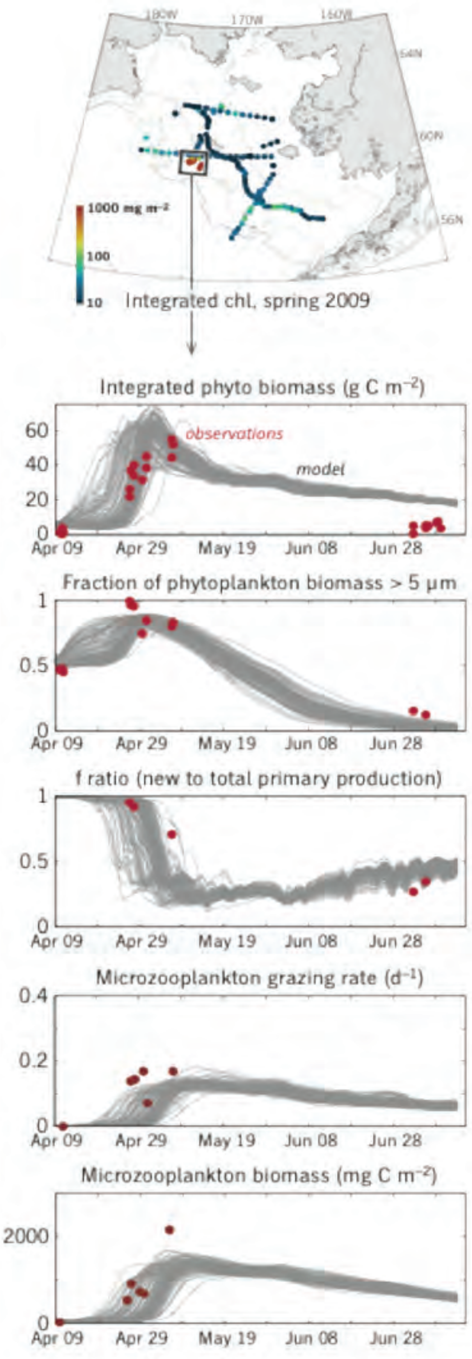
What if a future warmer ocean upsets this balance? We believe that one reason that the spring bloom is so productive is that it gets a jump on the zooplankton grazers, which are not very abundant after the long winter and cannot consume all of the primary production. A warmer ocean could result in tighter coupling between the planktonic producers and consumers with detrimental consequences for the benthic (sea floor) community.

Our planktonic ecosystem model indicates that large zooplankton have greater success in cold years in spite of, not because of, spring-summer conditions (Figure 2). In warm years, total primary and microzooplankton production are higher and warmer temperatures mean that growth and development of the large zooplankton are faster. Yet the large zooplankton have lower overall success in warm years. A new model of copepod life history tradeoffs is narrowing down the potential reasons for this. One idea is that warm winter temperatures decrease copepods' overwintering success by making them burn through their energy reserves too fast, but the model suggests that this direct temperature effect is outweighed by the positive effect of higher temperatures on spring-summer growth and development. Another idea is that cold years might favor the production of ice algae prior to the spring bloom.

Robert Campbell, University of Rhode Island
Carin Ashjian, Woods Hole Oceanographic Institution
Neil Banas, University of Washington
Evelyn Lessard, University of Washington
Alexei Pinchuk, University of Alaska Fairbanks
Barry Sherr, Oregon State University
Evelyn Sherr, Oregon State University
Jinlun Zhang, University of Washington

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Project and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



Model results. Time evolution of an intense ice-edge bloom, from spring-summer 2009 observations (red) and the model (gray). Gray lines show modeled community evolution along Lagrangian transport pathways that intersect the observed late April bloom; the spread among them shows the effect of small-scale patchiness and variability in ice-retreat timing. Observations are courtesy of the Mordy, Lomas, Sambrotto, and Sherr groups.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

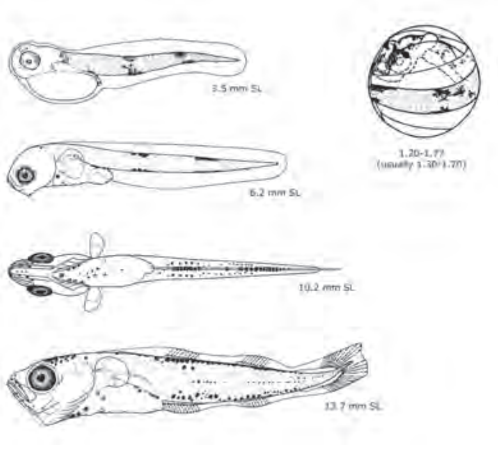
Does Water Temperature Influence Pollock Spawning?

INVESTIGATING "BOOM" AND "BUST" YEARS

Walleye pollock is a vital component of the food web in the Bering Sea, providing food for myriad fish, bird, and marine mammal species, as well as humans. But pollock management is challenged by notoriously variable spawning success and the subsequent survival of young pollock. In fact, the particular sequence of "boom" and "bust" years largely determines the success of the fishery and the ecology of the Bering Sea for many years. Spawning conditions influence a series of events that set year class strength.

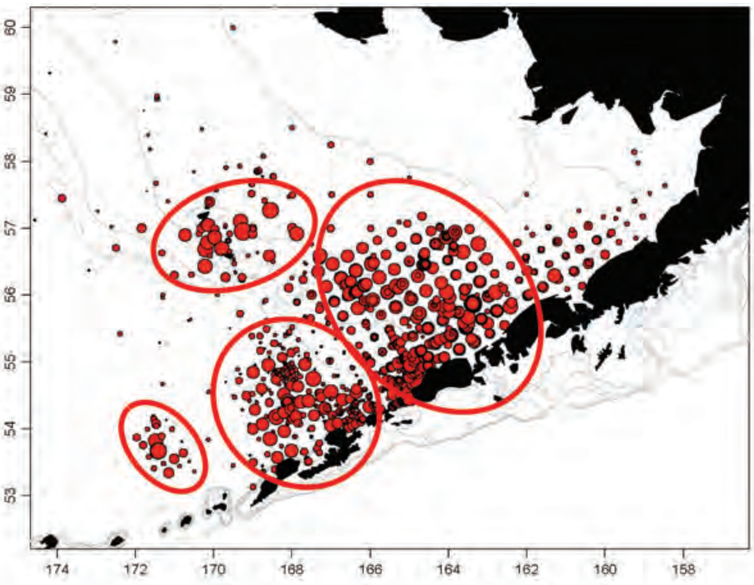
We suspected that variability in water temperature contributes to walleye pollock spawning success and changes of spawning distribution, suggesting that climate change could influence when and where pollock spawn. We were most interested in determining whether individual pollock conserve a memory of their previous or parental spawning locations or whether they exhibit flexibility in choosing their spawning sites. If we could understand how water temperature influences pollock spawning

continued on page 2



Illustrations by Beverly Vinter

Fig. 1



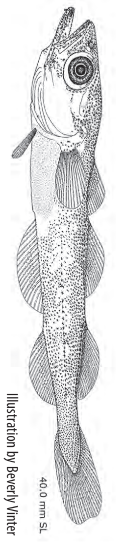


Illustration by Beverly Vinter

We found four areas of pollock spawning in the eastern Bering Sea based on long-term egg collections.

The Big Picture

Environmental variability is increasingly recognized as a regulator of marine fish spawning success and subsequent growth and survival of eggs and larvae. Using long-term egg collections and spawning adult catches, we examined the relationship between walleye pollock spawning distribution and success in relation to variability of spawning season (from March to May) and water temperature. Using a novel statistical analysis we predict that pollock spawning activity progresses from the Aleutian Basin to the shelf region of the Bering Sea from March to May. We also found that pollock spawning increases modestly throughout the study area as mean annual water temperature increases, but this increase is spatially homogeneous. So the overall spatial distribution does not change in relation to water temperature.

POLLOCK AND COD DISTRIBUTION
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

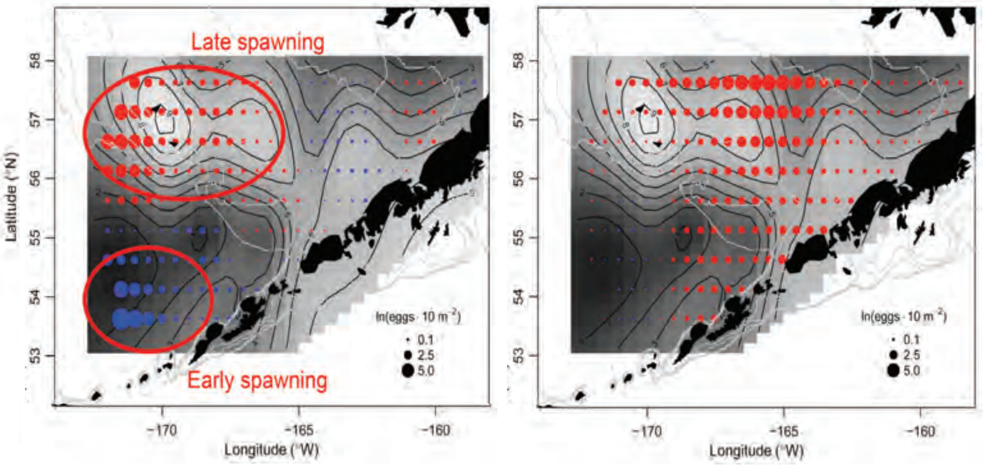
dynamics (abundance and distribution), then we could better predict the influence of climate change on the ecological dynamics of the Bering Sea.

How We Did It

We used a novel modeling approach to relate the catch of pollock eggs or spawning adults to progression of the spawning season and to water temperature, after accounting for other potential influences on pollock spawning. Data for this study consisted of 19 years of pollock egg and larval collections, as well as 22 years of adult pollock spawning season catch data. Our models allowed us to understand when and where catches of eggs or spawning adults increased or decreased under different conditions of water temperature. Here we only show data and results from egg catches, which are similar to those obtained from spawning adult pollock catches..

In the eastern Bering Sea, most pollock spawning activity occurs during spring (March to May). There are four main spawning aggregations (Fig. 1) going from the Aleutian Basin to the Pribilof Islands in the shelf region of the southeast Bering Sea. Pollock spawning progresses from the Basin in March to the shelf in May (Fig. 2). On average, pollock spawning is positively influenced by an increase of water temperature throughout the study region (Fig. 2). However, because the increase of spawning activity is spatially homogeneous, the distribution of pollock spawning does not change considerably in relation to changes of water temperature.

Fig. 2



Pollock spawning progressed from the Aleutian Basin in March to near the Pribilof Islands in May (left panel). Increased water temperature results in greater spawning activity but does not influence its location (right panel). The black contour lines and grey shading denote the average predicted egg density (from multiple years); darkest color corresponding to lower density. Overlaid on the image are red or blue bubbles, the size of which is proportional to an expected increase (red) or decrease (blue) of the egg density as time progressed from March to May (left panel), or as water temperature increases by one degree (right panel). Grey lines are bathymetric contours.

Why We Did It

Understanding the influence of a changing climate on pollock spawning is an important and timely topic of research because pollock is a key component of the Bering Sea food web and is heavily harvested. We were most interested in determining whether individual pollock conserve a memory of their previous or parental spawning locations or whether they exhibit flexibility in choosing their spawning sites. We found that environmental variability (e.g., temperature), while affecting the overall success, did not much alter the spatial assemblage of spawning locations, so we concluded that individuals do conserve a memory of their spawning sites and have limited flexibility to respond to interannual variations of environmental conditions.

Lorenzo Ciannelli, College of Earth, Ocean, and Atmospheric Sciences, Oregon State University

Nathan Bacheler, National Oceanic and Atmospheric Administration (NOAA) Southeast Fisheries Science Center

Kevin Bailey, NOAA Alaska Fisheries Science Center

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Circulation on the Bering Sea Shelf Revealed by Temperature and Salinity Measurements

AUGMENTING NOAA FISHERIES ANNUAL BOTTOM TRAWL SURVEY

Summer 2008-2010 measurements of the ocean currents inferred from mass density differences on the eastern Bering Sea continental shelf show predominantly northwestward flow (Figure 1). The current is strongest seaward of the 100-m depth contour that crosses the shelf from the Pribilof Islands (~57°N) toward St. Matthew Island (~60°N) giving a cross-shelf component to the flow. There are differences between the years. In 2008 and 2010, low-density water surrounding St. Matthew Island, probably due to sea-ice melt, suggests a clockwise circulation around the island. That less-dense lens was absent in 2009, and saltier, denser water intruded across the shelf to the 100-m contour. Measurements in 2010 went farther north and reveal dense water and implied flow entering Bering Strait (~65°N).

How We Did It

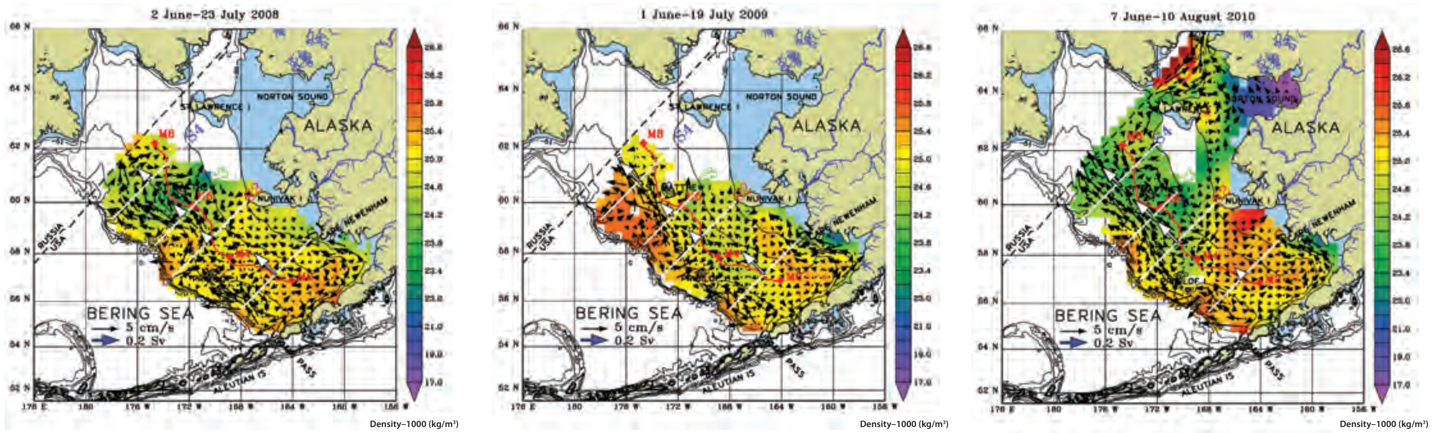
Ocean currents are driven by wind, tide and horizontal differences in the water's density (the

continued on page 2

The Big Picture

Unlike other sampling during the Bering Sea Project, the bottom-trawl survey CTD measurements are unique in two regards. The new measurements are made at no additional cost in ship time at established trawl sites where the ships are already scheduled to sample. Also, they cover the Bering Sea shelf on a uniform grid that is reoccupied annually, in contrast to process-oriented cruises that sail at varying times of the year and seek to study specific processes along scattered transects. This gives a shelf-wide scan of the temperature, salinity and density, providing new understanding of the geostrophic currents.

Fig. 1



Maps of geostrophic velocity vectors drawn on a colored background of seawater mass density at the sea surface for the summer bottom trawl surveys of 2008-2010, with purple denoting lower density and red higher density. White arrows show the geostrophic transport (in Sv = 10^6 m^3/s) across sections S1-S4. PMEL EcoFOCI mooring sites (M2, M4, M5 and M8) along the 70m isobath are plotted in red, and depths are contoured at 30, 50, 100, 200, 1000 and 2000 m.

Credit: Cokelet, E.D., 2014. 3-D water properties and geostrophic circulation on the eastern Bering Sea shelf. submitted to Deep Sea Research Part II: Topical Studies in Oceanography.

FISH FORAGE DISTRIBUTION AND OCEAN CONDITIONS
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

weight of a volume of water). Temperature and salinity together determine the density. Ocean water does not have the same density everywhere. Warmer, less-salty water is less dense than colder, saltier water. One might expect less-dense liquid to flow out over denser liquid until it reaches a uniform thickness and stops flowing, as seen in an exotic drink made with layered, colored ingredients. However, in the big ocean something else happens. The pressure force generated by horizontal differences in density can be balanced by the effects of the Earth's rotation, resulting in an ocean current. This is similar to the winds that circulate around a high-pressure system in the atmosphere. Such currents are called 'geostrophic' currents, from the Greek for Earth ('geo') and turning ('strophe'). In the northern hemisphere, the current flows with the low-density water on its right (when looking downstream), and the sea surface slopes upward to the right, as well. The flow is faster where the horizontal density difference is larger and extends over a greater depth.

Each summer NOAA's Alaska Fisheries Science Center conducts a bottom trawl survey, sampling fish at over 350 sites spaced 37 km apart to determine commercial fish stocks on the eastern Bering Sea continental shelf. We attach ruggedized CTD (conductivity-temperature-depth) instruments to the headropes of the bottom trawl nets to measure temperature and salinity profiles through the water column (Figure 2). From these measurements, we compute the water density at each site and then apply the known effect of the Earth's rotation to infer the current.

Fig. 2

A ruggedized CTD being attached to the bottom trawl net on the NOAA contract survey vessel F/V Arcturus.

Why We Did It

Ocean currents transport nutrients, plankton, fish eggs and larvae – important elements of the Bering Sea ecosystem. Adding CTD measurements to the existing bottom survey provides a relatively low-cost method with broad coverage to infer ocean currents. Those observations help us to understand the ecosystem, to measure its variability and to calibrate predictive computer models that estimate future conditions under different climate scenarios.

Edward D. Cokelet, NOAA Pacific Marine Environmental Laboratory

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Late Winter in the Northern Bering Sea

LOW PRODUCTION, BUT WIDESPREAD FORAGING OF STORED FOOD

It is well-known that the Bering Sea is productive, but it is also expected that the timing of productivity is tied to the availability of light. The availability of light to drive photosynthesis is related to both the return of sunlight as the spring equinox approaches, as well as the retreat of sea ice as winter's hold begins to ease. These are the expectations, but before the Bering Sea Project, conditions and animals using the northern Bering Sea (north of St. Matthew Island) in late winter were actually poorly known. We did know that the shallow shelf supports some of the most extensive marine invertebrate communities in soft sediments in the world ocean, and that certain specialized benthic-feeding predators, including walruses, spectacled eiders, and bearded seals, call these northern waters their winter home. How does this ecosystem function before the onset of the spring bloom? Where are these top predators foraging? What other birds are using these waters? Where there is open water within the ice (polynyas), is there enough light (and nutrients) to stimulate production?

How We Did It

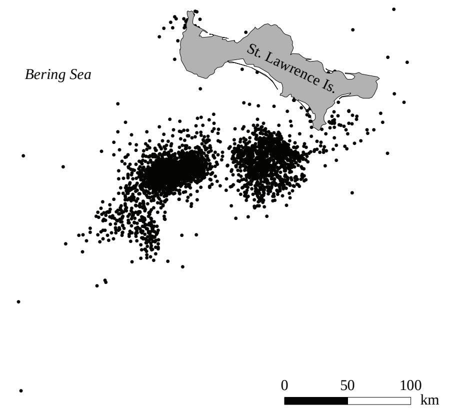
For three consecutive years (2008-2010), we had the extraordinary opportunity to sample the ice-covered northern Bering Sea in March and make observations of the water column, marine sediments and the animals living in this ecosystem. One of the objectives of the research was to determine where walruses and spectacled eiders were feeding on the sea floor,

continued on page 2

The Big Picture

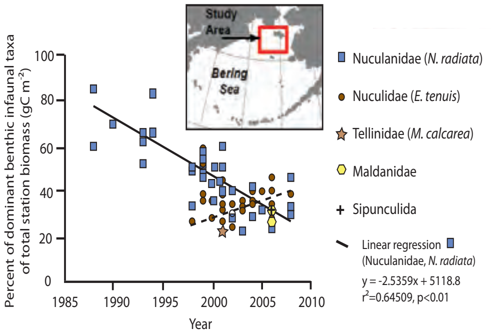
The Northern Bering Sea, roughly from St. Matthew Island north, is a distinct ecosystem that functions differently than the open seas to the south. This difference is particularly striking in the winter, when walruses, ice seals, and spectacled eiders congregate in large numbers to take advantage of abundant food supplies on the seafloor, and also, in some cases, from under-ice prey such as arctic cod and euphausiids. Productivity in the water column is low due to light limitations, but west-to-east decreases in chlorophyll and nutrients are already present, as they are later in the seasonal cycle when massive sea ice edge blooms occur. The biomass of the seafloor biological communities have been in decline over the past several decades, so additional changes in the ecosystem or the movement of industrial fishing northward may have negative consequences for the entire food web of the region.

Fig. 1



Spectacled eider satellite telemetry locations (n = 3,229) received from the primary wintering area in the Bering Sea south of St. Lawrence Island, Alaska in September-May in 2008-2009, 2009-2010, and 2010-2011. See Fig. 2 for study area inset map.

Fig. 2



Decline of clam populations in the prime spectacled eider winter foraging area south of St. Lawrence Island over the past several decades. Dashed line is possible (not statistically significant) increase since 2003 in Ennucula tenuis, *a bivalve species not favored by the eiders. Figure is modified from Grebmeier, 2012, Annual Review of Marine Science 4:63-78.*

BENTHIC ECOSYSTEM RESPONSE TO CHANGING ICE COVER IN THE BERING SEA
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

and to match that feeding with the distribution of food resources, as well as the ever shifting sea ice that might impact the ability of these air-breathing predators to return to the sea surface.

Why We Did It

The northern Bering Sea shelf is fundamentally different from more southerly Bering Sea shelves where commercial fisheries dominate. Cold bottom water temperatures influenced by ice formation are in part responsible for the ecosystem structure, which includes walruses, gray whales, and other bottom feeding predators that depend upon abundant biological communities on the seafloor. However, satellite observations indicate that the duration of seasonal sea ice, particularly north of St. Lawrence Island, is decreasing. Continuation of these patterns could bring fish north, as well as commercial interests. Industrial trawling could negatively impact these rich benthic communities that Yupik and Iñupiat communities on both St. Lawrence Island and the mainland depend upon indirectly through subsistence harvests of top predators such as walruses.

Lee Cooper, Chesapeake Biological Lab, University of Maryland Center for Environmental Science

Jackie Grebmeier, Chesapeake Biological Lab, University of Maryland Center for Environmental Science

Matt Sexson, USGS Alaska Science Center

Chad Jay, USGS Alaska Science Center

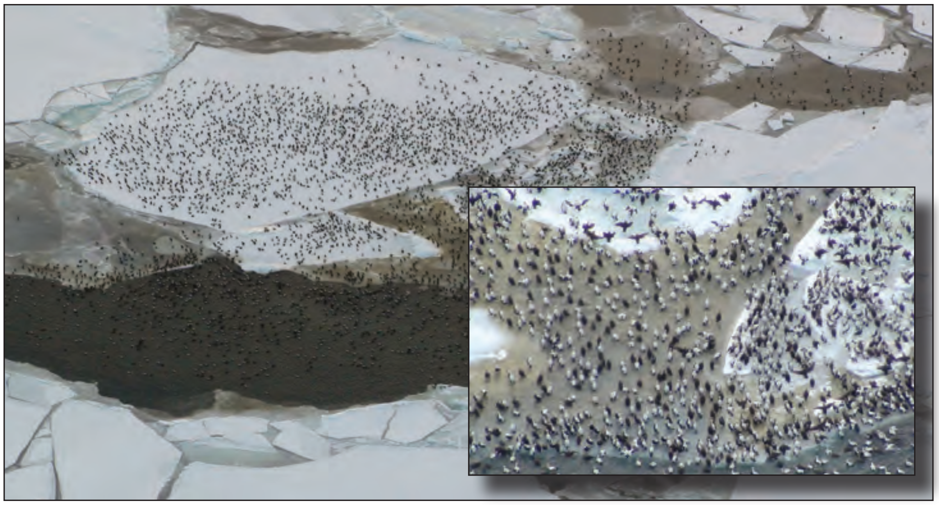
Anthony Fischbach, USGS Alaska Science Center

Jim Lovvorn, Southern Illinois University

Kathy Kuletz, US Fish and Wildlife Service

Cal Mordy, NOAA-University of Washington JISAO

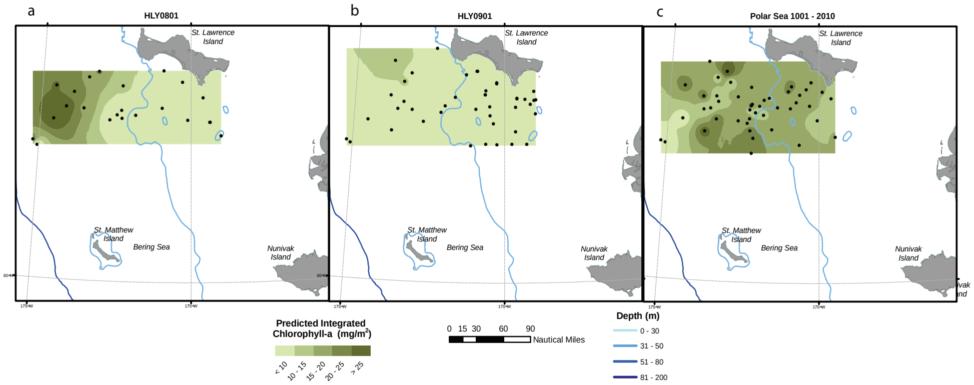
The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**



Both photos by Matt Sexson

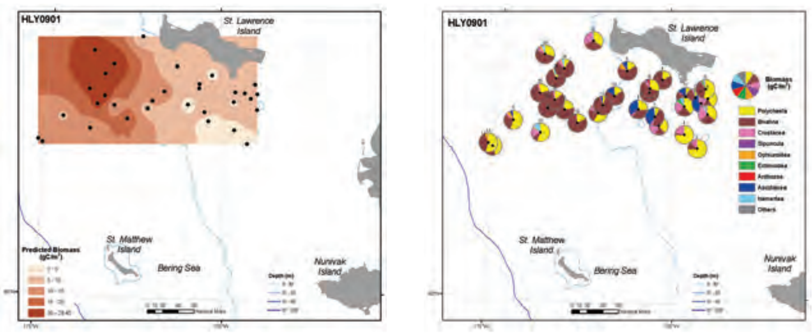
Spectacled eiders use openings in the sea ice of the northern Bering Sea to reach clam populations on the sea floor 40-60 m below. Other seabirds that use the open leads in winter and spring include black guillemot and Kittlitz's murrelet, which feed on small fish, euphausiids and amphipods that are aggregated at the ice edge. ***Inset:*** *A close-up view; spectacled eiders use the ice for rest between feeding bouts and use less energy to remain on the ice than to rest in the open water.*

Fig. 3



Predicted integrated Chlorophyll-a in the study area in March of 2008 (panel a), 2009 (b), and 2010 (c). Black dots are sampling stations. Water column chlorophyll (plotted in mg/m^2 over the whole water column) is characteristically one-to-two orders of magnitude lower than is observed during the peak of the spring bloom in May, but west-to-east decreases are also evident due to differences in water mass productivity and nutrient content.

Fig. 4



Benthic biomass per square meter (left) and dominance of clams (right, brown color in circles) from 2009. Note the alignment of clam populations with spectacled eider distributions determined using satellite telemetry (see Fig. 1).

BEST-BSIERP Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

New Insights into Bering Shelf Circulation Structure

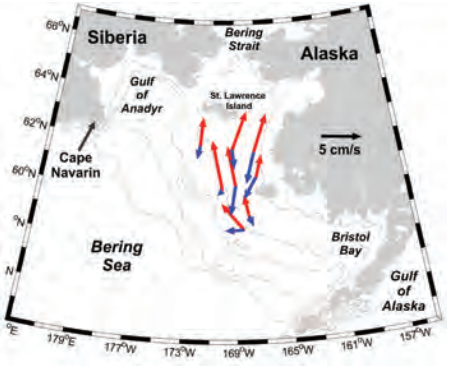
WINTER WIND DIRECTION ELICITS STRONG OCEAN CURRENT RESPONSE

Southeasterly winds (winds blowing from the southeast to the northwest) tend to promote shelf flow toward Bering Strait that originates south and east of St. Lawrence Island, and waters in the Gulf of Anadyr are more likely to flow west past Cape Navarin. In contrast, northwesterly winds tend to promote flow toward Bering Strait that originates west of St. Lawrence Island, while waters east and south of St. Lawrence Island reverse and flow southward. These results are applicable during winter months (October-April). During summer months (May-September), winds are lighter, the shelf stratification is stronger, and the flow field is more strongly controlled by other processes.

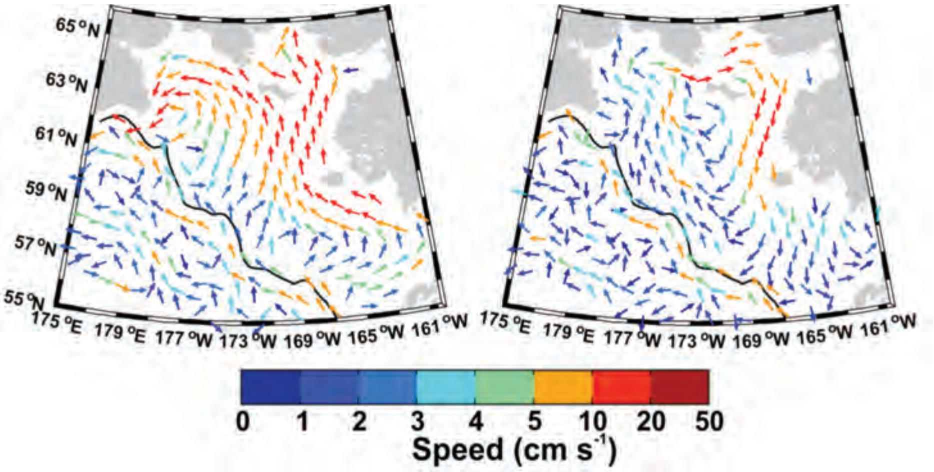
How We Did It

We deployed eight oceanographic moorings equipped with profiling current meters on the Bering Sea shelf from July 2008 to July 2010. Analysis of the current meter data in conjunction with the local wind field showed close connections between the winds and the currents.

continued on page 2



The Bering shelf. Vectors, emanating from the eight mooring deployment locations, show mean vertically averaged currents during southeasterly (red) and northwesterly (blue) winds from July 2008 - July 2010. Isobaths are drawn at 200, 100, 70, 50 and 20 m depth levels.



Vertically averaged hindcast current vectors from the 3D model for a month with strong southeasterly winds (December 2000, left) and strong northwesterly winds (December 1999, right). The shelfbreak (200 m isobath) is denoted with a black line.

The Big Picture

The Bering Sea ecosystem is fundamentally dependent upon the physical mechanisms and characteristics that determine the shelf habitat: ice extent and timing regulates light penetration into the water column and provides a seasonal platform for marine mammals; temperatures control metabolic processes and set limits on geographic distributions; currents carry zooplankton and fish larvae onto the shelf from the slope; frontal systems aggregate prey items; stratification in spring and wind mixing in fall promotes phytoplankton blooms. All of these processes depend in part on shelf currents.

STRATIFICATION ON THE BERING SHELF AND ITS CONSEQUENCES FOR NUTRIENTS AND THE ECOSYSTEM: THE EFFECTS OF ICE AND COASTAL WATER ADVECTION
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

UAF and UW mooring technicians David Leech, Kevin Taylor and Jim Johnson, with the assistance of Coast Guard personnel, prepare to deploy a bottom-anchored sub-surface taut wire mooring in July 2008. The mooring is held in place by a railroad wheel anchor; a large orange float provides buoyancy and houses the data loggers. This mooring made hourly measurements of temperature, conductivity, pressure, and currents until it was recovered in July 2009.

We were able to reproduce the basic nature of the observed current response using a very simple, "idealized" numerical model. More complex (fully 3-D) numerical models run in hind-cast mode demonstrate how the greater shelf circulation responds in areas far removed from the mooring array.

Why We Did It

A fuller understanding of the Bering Sea ecosystem requires knowledge of the continental shelf flow field and what controls it, because currents are responsible for conveying nutrients, plankton, eggs, and larvae from one place to another. Are nutrients carried onto the shelf continuously or in pulses? Do fish eggs or crab larvae get carried to the same places every year? Better knowledge of the circulation field and its variations will help us answer these questions.

Seth Danielson, Institute of Marine Science,
University of Alaska Fairbanks

Kate Hedstrom, Arctic Region Supercomputing Center, University of Alaska Fairbanks

Knut Aagaard, Polar Science Center, Applied Physics Laboratory, University of Washington

Tom Weingartner, Institute of Marine Science,
University of Alaska Fairbanks

Enrique Curchitser, Institute of Marine and Coastal Sciences, Rutgers University

---

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Young Fish in a Warm Bering Sea

THE FATE OF WALLEYE POLLOCK LARVAE

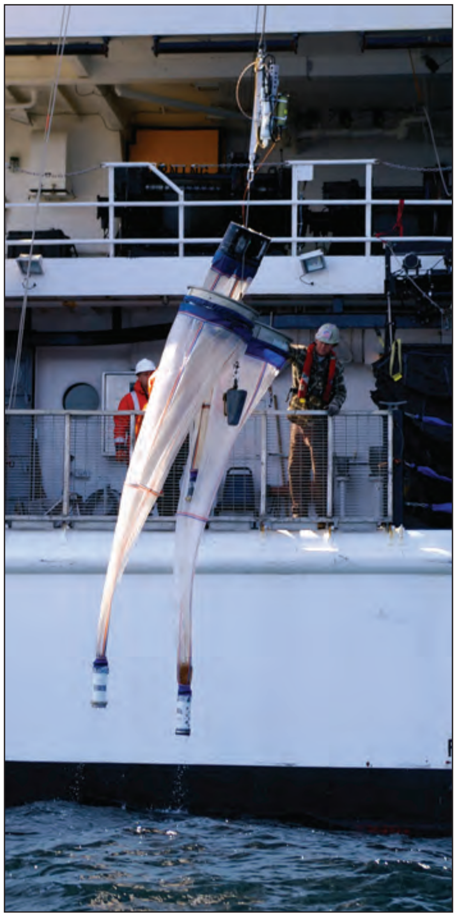
A single female walleye pollock can produce millions of eggs in her lifetime. If even three of her millions of potential offspring survive to adulthood, the female has not only replaced herself and her mate, but she has added one more to the overall population. In this case, population growth is positive. However, numerous factors act to cull the number of young that survive, and evidence suggests that walleye pollock populations are either stable or declining in the North Pacific. At the same time, there is mounting evidence for gradual warming in the Bering Sea, a major spawning area for walleye pollock. We asked the question, "Do warming conditions affect the survival of young walleye pollock? Do they affect their distribution? Their growth?"

How We Did It

We examined larval walleye pollock (*Gadus chalcogrammus*) distribution and abundance under colder-than-average and warmer-than-average conditions in the Bering Sea. To examine long-term trends, we relied on a series of historical samples collected by the National Oceanic and Atmospheric Administration/Alaska Fisheries Science Center (NOAA/AFSC) Fisheries Oceanography and Coordinated Investigations program. NOAA has been conducting plankton surveys in the eastern Bering Sea since the mid 1980's. Fish eggs and larvae (ichthyoplankton) are collected with small mesh nets that strain ocean water and accumulate the early life stages of fish (Figure 1). Samples were preserved and identified, and data were archived in a database of larval fish collections. We used database-derived data on walleye pollock eggs, larvae, and early juveniles collected on plankton surveys conducted between 1988 and 2010 to calculate the mean geographic center-of-distribution for eggs, larvae, and juveniles over the continental shelf during warm periods and cold periods. We also determined mean size of pollock larvae and mean mortality rates during warm and cold periods. Finally, we examined shifts in the timing of peak egg abundance to address

continued on page 2

Fig. 1



Walleye pollock eggs and larvae are collected using small mesh plankton nets.

The Big Picture

Our study demonstrates that shifts in ocean temperatures affect young walleye pollock larvae both directly and indirectly. Direct impacts include growth effects, metabolism, and development. Indirect effects include temporal shifts in the timing of spawning and climate-mediated influences on ocean currents that deliver larvae to nursery areas. Our conclusion: future changes in ocean temperatures will alter rates of growth, development, and survival of pollock larvae, and can contribute to eastward shifts in the distribution of eggs and larvae.

ICHTHYOPLANKTON SURVEYS
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

the hypothesis that the timing of pollock spawning may be delayed under cold conditions.

What we found:

- There is evidence of a shift in the timing of spawning of adult walleye pollock by as much as 30 days between warm and cold years, with timing of peak egg abundance occurring in March in warm years and April in cold years.
- All stages of larval walleye pollock were distributed over the middle shelf in warm years and over the outer shelf in cold years (Figure 2).
- Mean growth rates of larval walleye pollock were reduced in cold years relative to warm years (Figure 3a).
- Mean mortality rates of larval walleye pollock were elevated in cold years relative to warm years (Figure 3b).

Why We Did It

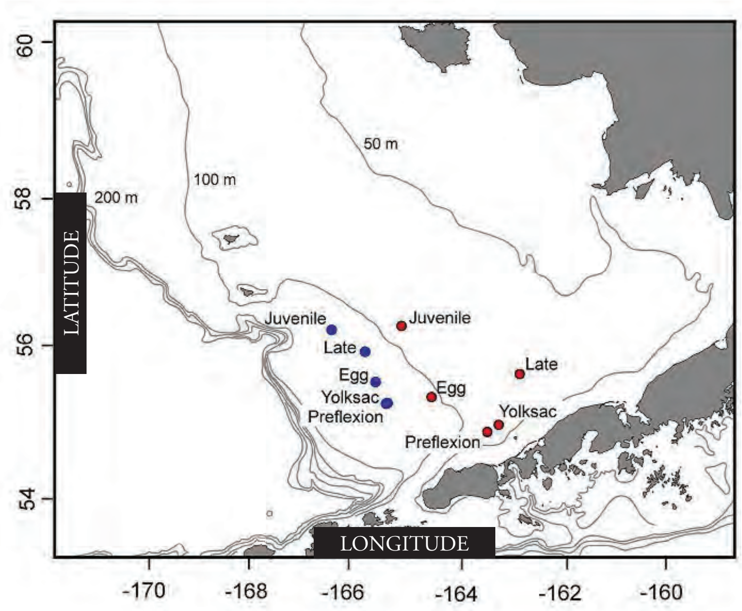
Walleye pollock larvae hatch out relatively underdeveloped, lacking the fins that promote swimming abilities, so they tend to be transported at the mercy of predominant ocean currents. Climate-mediated shifts in ocean flow deliver larvae to different habitats during warm and cold periods, potentially affecting the type and densities of zooplankton prey that developing larvae need for growth and survival. This is important for young fish since survival to the juvenile phase of life is a critical step in successful recruitment to the fishery.

In addition, fast growing larvae that occur at warm temperatures have higher metabolic requirements, necessitating access to ample, high quality prey resources to sustain good growth. However, other work has determined that the zooplankton prey available to walleye pollock larvae in warm years is of poorer quality than that available in years when temperatures are cold. Prolonged feeding by fast-growing larvae on low-quality prey jeopardizes overall survival and recruitment. In fact, recent evidence suggests that fewer pollock larvae ultimately survive to become 1-year olds when conditions were warm during the larval period compared to when they were cold.

Janet Duffy-Anderson, NOAA/AFSC
Franz Mueter, University of Alaska Fairbanks (UAF)
Tracey Smart, University of Washington (UW)
Elizabeth Siddon, UAF
John Horne, UW

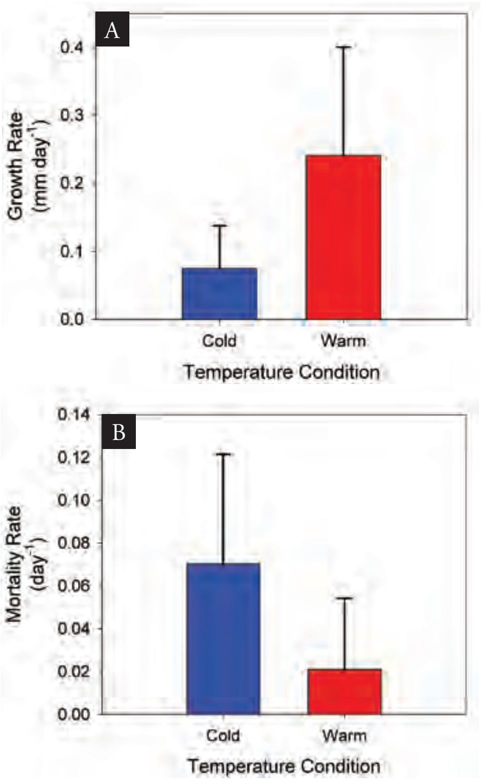
The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



Distributions of all early life history stages (eggs, yolksac larvae, preflexion larvae, postflexion larvae, juveniles) of walleye pollock are shifted eastward over the middle continental shelf in warm years and westward over the outer continental shelf in cold years.

Fig. 3



Larval growth rates (A) are reduced in cold years relative to warm, and larval death rates (B) are increased in cold years relative to warm.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Hidden Food in the Coldest of Times

THE NUTRIENT ROLE OF SEA ICE

Copepods, tiny lipid-rich crustaceans in the Bering Sea, are a favored meal of larval and juvenile Pollock. One copepod that dominates the zooplankton on the Bering Sea shelf, and shelf areas around the Arctic Ocean, is *Calanus glacialis* (Figure 1). We know that the abundance of this species fluctuates between years. Surprisingly, colder years, when ice cover is more extensive and persists longer during spring, appear to favor growth of the copepod population. Why is this? We set out to answer this question during a cruise in late winter of 2009 through early spring of 2010, when ice covered most of the Bering Sea shelf.

Since reproduction and growth of this copepod is controlled by the availability of food, we thought that they must be obtaining sufficient food under the ice to initiate feeding and reproduction. A second question is "what is this food source"? One possibility was the layer of ice algae—a diverse community of microscopic plants and animals that grow under the ice during spring (Figure 2)—rather than from the more usual phytoplankton community in the water column beneath.

How We Did It

We collected zooplankton samples to see what the *C. glacialis* population was doing, whether the adult females were laying eggs or not, and how much food was in their guts. We determined the identity of individual prey species in their guts from their DNA and quantified the amount of this

continued on page 2

Fig. 1

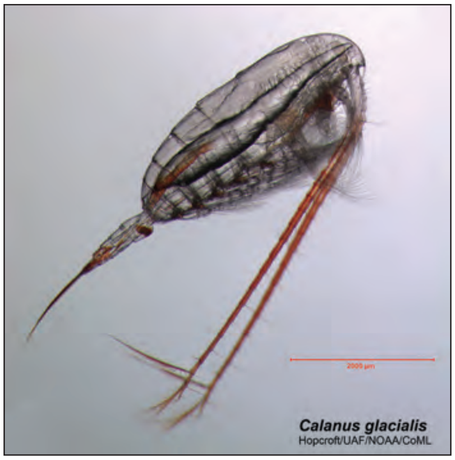
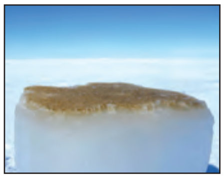


Fig. 2

Blocks of sea ice turned upside down to reveal a thick layer of ice algae.



The Big Picture

The high feeding rates of the copepod *Calanus glacialis* that we observed during a cruise in late winter and early spring of 2009/2010 could not have been sustained by the low levels of phytoplankton in the water column. This, and the presence of ice algae found in their guts, indicates that the copepods were obtaining their nutrition from ice algae. The higher feeding rates appeared to be associated with warmer air temperatures, which are, in turn, associated with the release of ice algae into the water. Before this ice algae is diluted by dispersion into the water column below, it is likely that it provides a dense layer of food for the zooplankton. In years when when ice cover is more extensive and persists longer, there is an extended period of higher food availability for *C. glacialis*, compared with the brief ice-edge or water column phytoplankton bloom. This results in a longer period of population growth, resulting in greater abundance later during the spring.

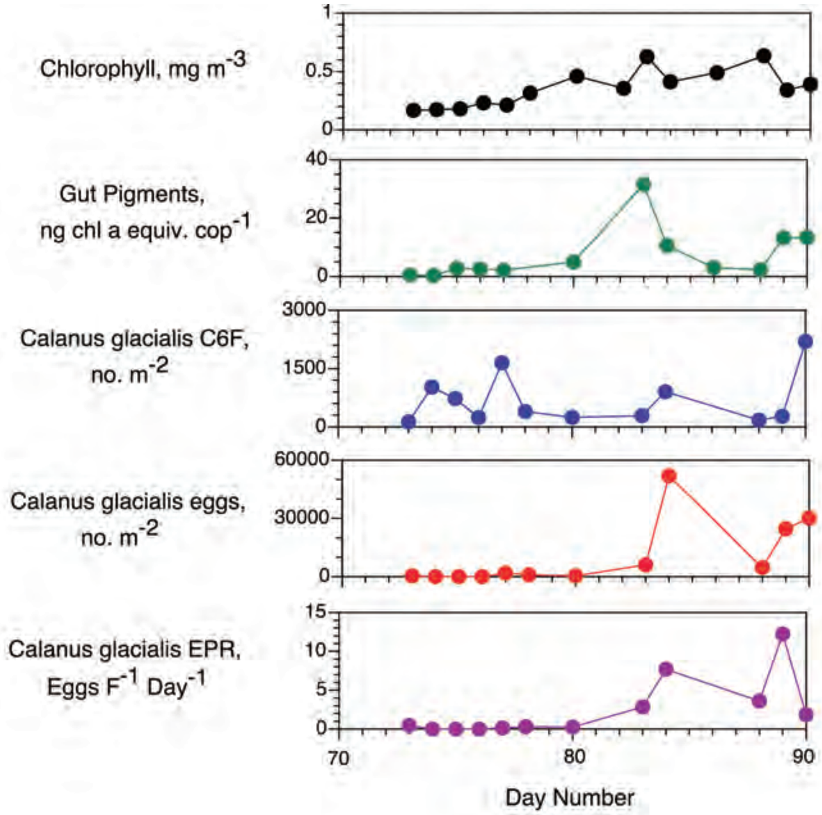
A NOVEL MOLECULAR APPROACH TO MEASURING IN SITU FEEDING RATES OF COPEPODS IN THE SOUTH EASTERN BERING SEA
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

prey DNA to calculate consumption (Figure 3). The amounts of phytoplankton chlorophyll in their guts provided an independent measure of consumption (Figure 4). We also measured the amount of phytoplankton present in the water column beneath the ice, and used DNA analysis to characterize the potential prey species present both in the water column and in the ice algal community growing on the underside of the ice.

What we found:

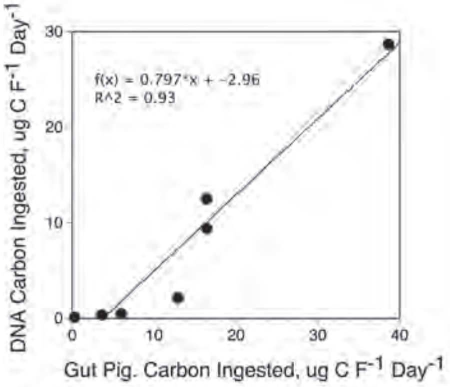
- *We found phytoplankton in extremely low concentrations within the water column under the ice, while a dense layer of ice algae was at the base of the ice at most locations.*
- C. glacialis *eggs began to appear in the water column during the cruise. At the same time we found large amounts of phytoplankton chlorophyll in the guts of adult female* C. glacialis, *indicating elevated feeding rates.*
- *The prey DNA in the guts of* C. glacialis *was mostly from ice algal species, indicating that ice algae were an important source of food.*
- *Quantification of this prey DNA followed the same pattern of variation over time as the chlorophyll a pigments, indicating that DNA can be used to provide a measure of feeding rate on individual prey species.*

Fig. 3



Mean water column chlorophyll a, Calanus glacialis *adult female gut pigments, abundance, egg abundance in the water, and estimated egg production rates between March 17 (Day 70) and March 31 (Day 90) 2010.*

Fig. 4



Estimated daily consumption by Calanus glacialis *adult females of the four diatom prey species, based on the 18S DNA copy numbers in their guts, plotted against estimated phytoplankton consumption, based on gut pigments.*

Why We Did It

Population growth of the dominant Arctic copepod *C. glacialis* appears to be dependent upon seasonal ice cover and its associated ice algae during spring. Changes in the extent of this seasonal ice cover associated with climate change will adversely affect higher trophic levels that feed upon this key species. The Bering Sea Shelf is a region of rapid climate change. Knowledge of how key species respond to this change will help predict overall ecosystem response, and how important fisheries, as well as endangered species, may be affected.

Edward Durbin, University of Rhode Island Graduate School of Oceanography

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Subsistence Harvests Show Continuity and Change

HARVESTS REFLECT ECOSYSTEMS AND SOCIETY

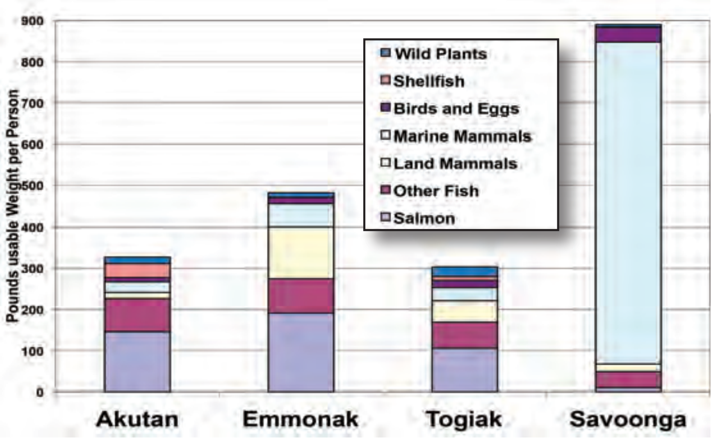
Our work documented relatively high and diverse subsistence harvests, consistent with earlier research and confirming the continuing economic, social, and cultural importance of subsistence uses of wild resources. The research also found differences in subsistence use patterns compared to previous years' studies, such as harvest levels, harvest composition, and diversity of resources used. The nature of these differences varied among communities, with some increases and some decreases, suggesting local influences in addition to potential region-wide changes. Survey respondents identified a complex range of personal, economic, and environmental factors when comparing subsistence uses in the study year with previous years. These factors included increasing costs of fuel and purchased food, commercial fisheries harvests and bycatch, more persistent storms and less predictable winds, and reduced sea ice. Such conditions affect resource abundance and locations as well as access to fish and wildlife populations, and may shape long-term trends. So far, as in the past, families and communities have adapted to changing economic, social, and environmental conditions, but

continued on page 2

The Big Picture

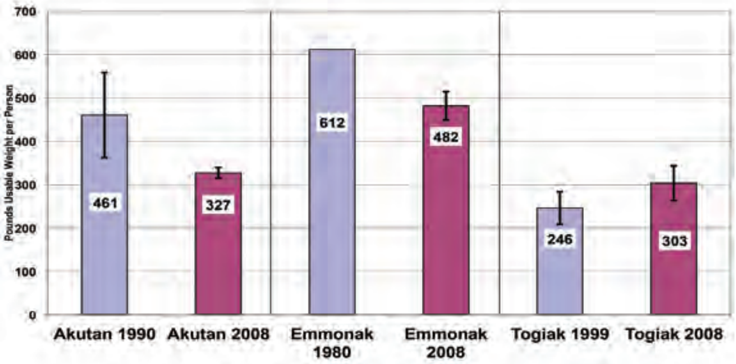
Alaska's Bering Sea coasts and islands are home to Aleut, Yup'ik, Iñupiaq, and St. Lawrence Island Yupik peoples. Their subsistence practices are essential to their cultures, heritage, and well-being, and are recognized by customary rights and by various laws and policies. An integrated study of the Bering Sea ecosystem is incomplete without understanding the people whose ways of life are part of the stunning ecological and cultural richness and diversity of the region. In addition, the findings of such a study are of great importance to those whose lives and livelihoods are most directly affected by changes in that ecosystem.

Fig. 1



Subsistence harvests of fish, wildlife, and wild plants, pounds usable weight per person, in the study communities in 2008. These substantial harvests provided between 170% (Togiak) and 500% (Savoonga) of daily protein requirements for community residents.

Fig. 2



Akutan, Emmonak, and Togiak: total subsistence harvests in pounds per person in 2008 compared to previous study years.

SUBSISTENCE HARVEST, USERS AND LTK ECOSYSTEM PERSPECTIVE
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

Alaska Department of Fish & Game

Local research assistant Daisy Lamont interviews an Emmonak family about their subsistence harvests.

Antone Shelikoff

Sockeye salmon drying on racks, Akutan.

Alaska Department of Fish & Game

Jars of oil rendered from sea lion (left) and harbor seal, Akutan.

the future is less clear if such changes intensify or accelerate. Local community residents should be essential partners in future efforts to understand these complex processes that affect the natural resources of the Bering Sea.

How We Did It

To document and quantify subsistence harvests of fish and wildlife resources, comprehensive household harvest surveys were conducted in four Alaska Native communities on the Bering Sea: Akutan, Emmonak, Savoonga, and Togiak. The surveys used a detailed questionnaire to ask participants about their subsistence activities in the previous year (see Figs. 1 and 2). In addition, interviewers asked open-ended questions about factors affecting subsistence, trends in the community and the ecosystem, and other topics that provided insight to help explain harvest patterns (example responses are shown in blue boxes below). In a fifth community, St. Paul, annual programs to document two key subsistence resources, fur seals and sea lions, were continued, revealing trends at an annual level.

Why We Did It

Hunting, fishing, and gathering have provided food for Alaska Native communities since time immemorial. They continue to play a major role in nutrition, culture, identity, and social connectivity within and among communities. Subsistence is thus a major part of human use of the Bering Sea ecosystem. Understanding subsistence patterns is crucial to documenting how people use and interact with their environment, what those interactions mean for individuals and communities, and how social and ecological change may be affecting people.

James A. Fall, Alaska Department of Fish and Game, Division of Subsistence, Anchorage

Nicole M. Braem, Alaska Department of Fish and Game, Division of Subsistence, Fairbanks

Caroline L. Brown, Alaska Department of Fish and Game, Division of Subsistence, Fairbanks

Lisa B. Hutchinson-Scarbrough, Alaska Department of Fish and Game, Division of Subsistence, Anchorage

David S. Koster, Alaska Department of Fish and Game, Division of Subsistence, Anchorage

Theodore M. Krieg, Alaska Department of Fish and Game, Division of Subsistence, Dillingham

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Traditional values continue to shape subsistence hunting and fishing activities in the study communities. As a resident of Togiak explained:

"My grandparents used to tell me that the things I got from this land and water don't belong to me. It was given to me to use and to respect it all the time. The first rule from my grandpa is take only what you can use. Even if there is abundance of whatever take only what you can use, what you can handle. Never waste, and respect the animals, so like with the fish, they can come back year after year after year."

A very active hunter and fisherman from Akutan described changing weather patterns that have impeded subsistence activities.

"Storms are more frequent and less predictable. For example, the usual pattern, up to a few years ago, would be a big storm with lots of wind that would stay a few days, then would clear for a few days before the next would come. Lately, the last couple of years, the storms seem to come back-to-back and are mixed with each other. This makes it harder for us to get out and hunt because the storms make the sea too dangerous."

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Whales and Porpoise in the Bering Sea

CHANGES WITH TEMPERATURE

The Bering Sea has gone through significant environmental changes over the past decades, some of which may be driven by global warming. Understanding distribution and abundance is important for evaluating how these changes will influence the habitat and behavior of cetaceans (whales, dolphins and porpoise). Also, because year-to-year variation in ocean temperatures and productivity has been shown to affect their prey of zooplankton and schooling fish, determining how cetaceans interact with their environment will help predict how they will respond to these changes.

Our study shows that the abundance and distribution of cetaceans changed with the temperature of the environment. In colder years, there were more whales and fewer porpoise in our study area (Figure 1). The distributions of humpback (*Megaptera novaeangliae*) and fin whales (*Balaenoptera physalus*) were similar regardless of temperature, but the distributions of minke whales (*B. acutorostrata*), Dall's (*Phocoenoides dalli*) and harbor porpoise (*Phocoena phocoena*) seemed to shift toward deeper waters in colder years (Figure 2).

How We Did It

As part of NOAA's walleye pollock (*Gadus chalcogrammus*) assessment cruises, we conducted surveys in 2002, 2008 and 2010 on the eastern Bering Sea shelf. When we saw a group of cetaceans, we recorded the location, the species and the number of individuals. We plotted sightings to examine the distribution of each species. Five cetacean species (humpback, fin and minke whales, Dall's and harbor porpoise) were seen in sufficient numbers to also estimate abundance and to evaluate whether numbers changed over time. We computed the abundance of these species by estimating how many groups were seen within a certain distance from the ship and extrapolating to the whole survey area. Finally, we estimated changes in abundance between 2002 and 2010 using traditional regression methods.

continued on page 2

Fig. 1

	2002 (Warm)	2008 (Cold)	2010 (Cold)	Trend
Humpback Whales	231 (39 to 1370)	436 (177 to 1073)	675 (150 to 3040)	12.0% (-9.8% to 34.0%)
Fin Whales	419 (219 to 802)	1368 (695 to 2692)	1061 (493 to 2283)	14.0% (1.0 to 26.5%)
Minke Whales	389 (147 to 1030)	517 (146 to 1831)	2020 (520 to 7855)	15.6% (-6.2% to 38.6%)
Dall's Porpoise	35,303 (12,989 to 95,946)	14,543 (7598 to27,837)	11,143 (5788 to 21,451)	-14.4% (-29.0% to 1.0%)
Harbor Porpoise	1971 (798 to 4870)	4056 (1844 to 8920)	833 (230 to 3018)	-0.7% (-33.6% to 24.9%)

Estimated abundance by species and year, with 95% confidence intervals in parentheses.

The Big Picture

We examined the Bering Sea Project hypothesis that climate and ocean conditions will affect cetacean prey and, consequently, will influence cetacean foraging habits. Will whales remain in their typical feeding areas in years when their prey is not as abundant? Because other studies have found that prey populations change with ocean temperature, we use temperature as a proxy for change in cetacean prey and foraging habitats. We examined the distribution and quantified the abundance of whales and porpoise in warm and cold years and by oceanographic domain. Our conclusion: the abundance of whales increased in cold years, which corresponds to periods when higher abundance of their potential prey seems to occur as revealed by other Bering Sea Project studies on zooplankton and fish. The abundance of porpoise decreased in cold years, but the reasons are not yet fully understood.

WHALE BROAD-SCALE DISTRIBUTION
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

What We Found

Humpback whales were more concentrated in coastal waters along the Alaska Peninsula and fin whales occurred primarily in the outer continental shelf. Minke whales were scattered throughout the eastern Bering Sea. Dall's porpoise were more common in the outer shelf and harbor porpoise were found in both outer and middle domains. We found evidence that the abundance of baleen whales increased over the study period, but the abundance of porpoise declined or remained constant.

Why We Did It

The distribution of cetaceans in high latitudes, including the Bering Sea, is assumed to be driven by the distribution of their prey. We suspect that the abundance of cetaceans and their preferred habitats will vary in time and space if the composition and energetic value of their prey changes. Profound effects on the distribution and abundance of large marine predators like whales are expected if climate change causes prolonged periods of warmer conditions in the Bering Sea. For this reason, information on current cetacean occurrence and population size is necessary for interpreting future changes.

Nancy A. Friday, NOAA Alaska Fisheries Science Center (AFSC), National Marine Mammal Laboratory (NMML)

Alexandre N. Zerbini, NOAA AFSC NMML and Cascadia Research Collective

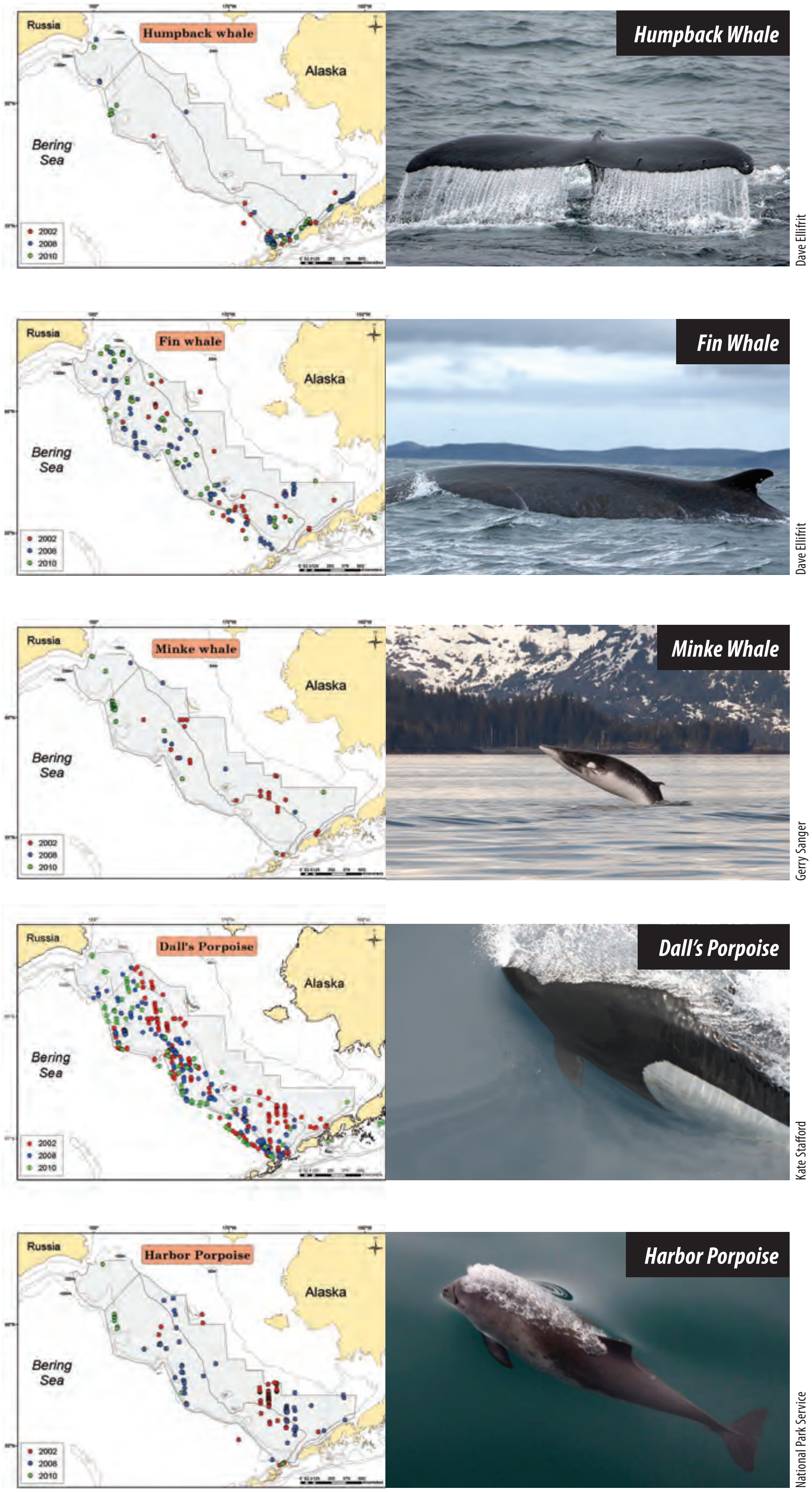
Janice M. Waite, NOAA AFSC NMML

Sue E. Moore, NOAA, Office of Science & Technology, Marine Ecosystems Division

Phillip J. Clapham, NOAA AFSC NMML

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



Dave Ellifrit

Dave Ellifrit

Gerry Sanger

Kate Stafford

National Park Service

Sightings of the five cetacean species in the study area, by year—red dots for 2002, blue for 2008, green for 2010.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

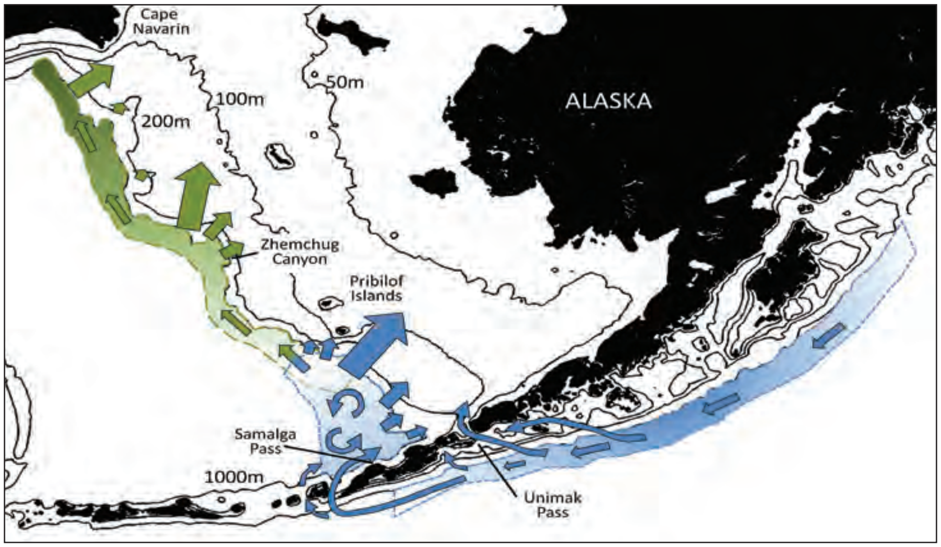
Where You Are Is More Important Than Where You Started

WINDS PROMOTE THE TRANSPORT OF OCEANIC ZOOPLANKTON ONTO THE BERING SEA SHELF, BUT IN-SITU PROCESSES MAY CONTROL THEIR SHELF BIOMASS

On-shelf transport of oceanic zooplankton onto the eastern Bering Sea shelf is elevated around submarine canyons traversing the shelf break, and around Cape Navarin in the northern Bering Sea (Figure 1). The extent of on-shelf transport depends primarily on wind direction. Southeasterly winds that blow along the Bering Sea shelf break from January-April result in increased on-shelf transport along the length of the shelf break (Figure 2), but reduced transport at the northern end of the shelf break around Cape Navarin; northwesterly winds have the opposite effect (Figure 3). Southeasterly winds are generally associated with warmer air temperatures, while northwesterly winds are associated with colder air temperatures. Net tow observations of zooplankton abundance on the Bering Sea shelf indicate that *Neocalanus* spp. abundance and biomass actually increase in cold years. The cold years examined did not stand out as having periods of strong SE wind, which promotes on-shelf flow during January-April, a critical time period for transportation of seasonally migrating larvae. This suggests that changes in oceanic

continued on page 2

Fig. 1



Conceptual diagram of oceanic zooplankton transport pathways onto the eastern Bering Sea shelf. Shaded regions indicate likely source areas for oceanic zooplankton, which remain relatively constant despite inter-annual variability in wind direction. Shading intensity indicates likelihood that a region supplies zooplankton to the southern (blue) and the northern (green) Bering Sea shelf. Arrow size indicates relative transport volume.

The Big Picture

Zooplankton are a major link in the food chain of the Bering Sea shelf. Therefore, the species composition, and the abundance of zooplankton over the shelf can impact the pelagic community at a variety of trophic levels, from fish to birds and marine mammals. The distribution of zooplankton species on the shelf is influenced by processes moving water masses, along with their constituent zooplankton communities, onto and off of the shelf. Our findings suggest that transport of the zooplankton onto the shelf appears to be enhanced in the vicinity of canyons and that wind direction is the primary driver in determining the on-shelf transport of large oceanic zooplankton that inhabit the upper wind-mixed layer for much of their life cycle. However, the success of oceanic zooplankton once on the shelf will depend on conditions encountered, i.e. the amount of food they find and the predation they experience. It appears that these in-situ conditions must be at least as important as transport processes in determining the biomass of oceanic zooplankton over the shelf.

DOWNSCALING GLOBAL CLIMATE PROJECTIONS TO THE ECOSYSTEMS OF THE BERING SEA WITH NESTED BIOPHYSICAL MODELS
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

zooplankton biomass on the shelf may be more dependent on in-situ processes promoting growth and survival than mechanisms promoting transport. Despite inter-annual differences in the magnitude of on-shelf transport, the relative importance of source areas to supplying zooplankton to the Bering Sea shelf did not vary greatly from year to year (Figure 3). A relatively consistent supply of oceanic copepods to the outer shelf of the southern Bering Sea produces a favorable foraging habitat for higher trophic levels.

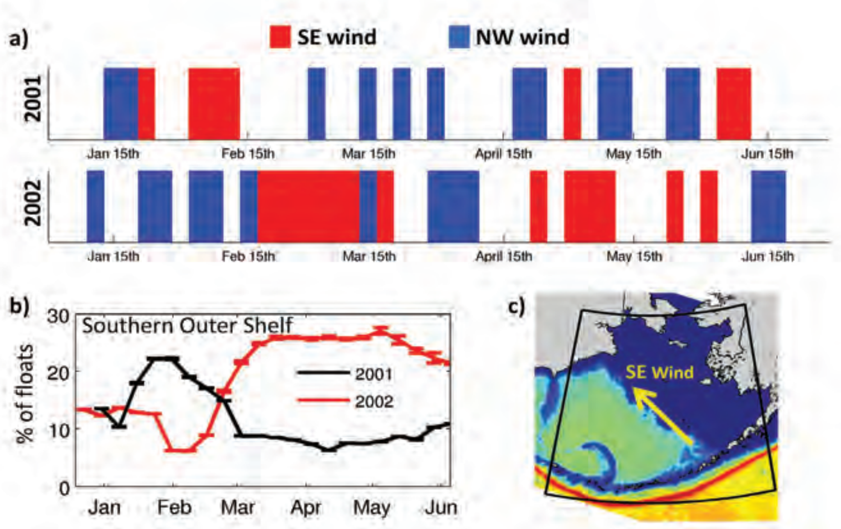
How We Did It

Using a three-dimensional oceanographic model, coupled to a model of 'virtual' floats, designed to have ontogenetic vertical migration behavior similar to the large-bodied oceanic zooplankton *Neocalanus*, we explored the mechanisms, timing and location of the transport of *Neocalanus* onto the eastern Bering Sea shelf from overwintering sources along the Gulf of Alaska and Bering Sea shelf breaks. Float trajectories resulting from alternate climate forcing scenarios were compared to determine which environmental variables and conditions were most influential in controlling cross-shelf transport.

Why We Did It

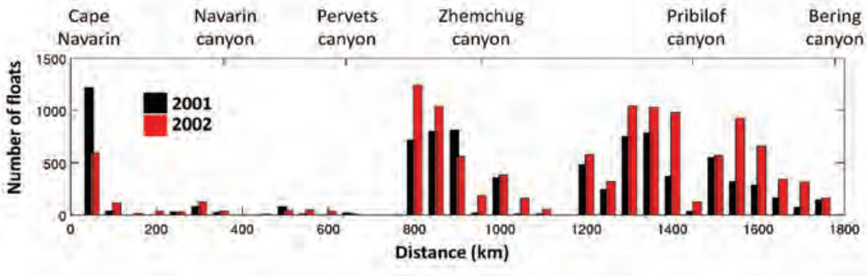
The Eastern Bering Sea shelf is divided into distinct hydrographic domains by structural fronts. Despite frontal obstructions to cross-shelf transport, each year large oceanic copepods—primarily *Neocalanus* spp.—are known to dominate the biomass of the outer-shelf zooplankton communities, and in some years are advected into the middle-shelf domain; the mechanisms promoting on-shelf transport of oceanic zooplankton were poorly understood. The oceanic zooplankton are an important prey source for higher trophic levels such as birds, whales and commercially important fish. Inter-annual variability in environmental conditions promoting shoreward transport of oceanic zooplankton onto the outer Bering Sea shelf have the potential to affect energy transfer and food web relationships throughout the Bering Sea shelf.

Fig. 2



a) Predominant wind direction in 2001 and 2002. Blue indicates NW wind while red indicates SE wind. b) Percentage of all floats released that were on the Bering Sea Southern Outer Shelf from January through June in 2001 (black) and 2002 (red). c) Domain over which the wind direction index shown in (a) was computed.

Fig. 3



Number of virtual zooplankton floats first crossing the 200m isobath at 50 km binned locations along the length of the Bering Sea shelf break, from the northern end of the shelf (Cape Navarin) to the southern end (Bering canyon) for 2001 (black) and 2002 (red). In both years, a total of 21,240 floats were released at 700m depth along the 1000m isobath.

G.A. Gibson, International Arctic Research Center, University of Alaska, Fairbanks

K.O. Coyle, Institute of Marine Science, University of Alaska, Fairbanks

K. Hedstrom, Arctic Region Supercomputing Center

E. N. Curchitser, Institute of Marine and Coastal Sciences, Rutgers University

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Bering Sea Ice

LIFE IN THE FREEZER

While life in association with sea ice has been studied for hundreds of years in many Arctic and Antarctic regions, very little information had been gathered from the Bering Sea. This is surprising, as the Bering Sea has the largest seasonal sea ice extent of any Arctic region. Our group focused on the biological activity within the sea ice, trying to understand the amount and fate of primary production contributed by tiny algae living within the sea ice.

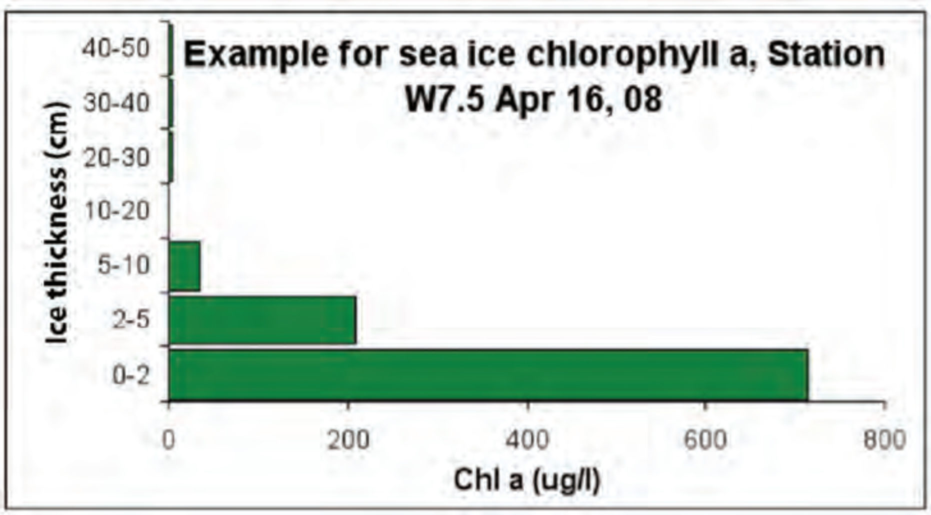
We discovered that each spring vast amounts of sea ice algae accumulate in highly concentrated thin bottom layers of the sea ice floes (Figure 1), and we observed concentrations of algae within these layers that exceeded water column phytoplankton concentrations by a factor of 100 to more than 1,000 from mid-March to the end of June. The total amount of plant biomass within the bottom 10 cm of the ice is about the same as for the phytoplankton integrated over the upper 20 m of the water column. During the ice covered period, pelagic crustaceans, mainly the euphausiid *Thysanoessa raschii* (sometimes known as Arctic krill) is likely ingesting sea ice algal material. With the onset of ice melt, the ice algal biomass was rapidly released into the water column and helped support the food webs in the water column and at the seafloor.

How We Did It

During expeditions in spring 2008, 2009, and 2010 we sampled dozens of different ice floes (Figure 2), at various locations, for the sea ice algal abundance and growth rates. Sea ice samples were taken with a specialized ice corer (Figure 3). Back on the ship, ice cores were melted and the melted samples were analyzed for concentration of algal pigments, mainly chlorophyll *a*. We compared these data to the algal development below the sea ice by

continued on page 2

Fig. 1

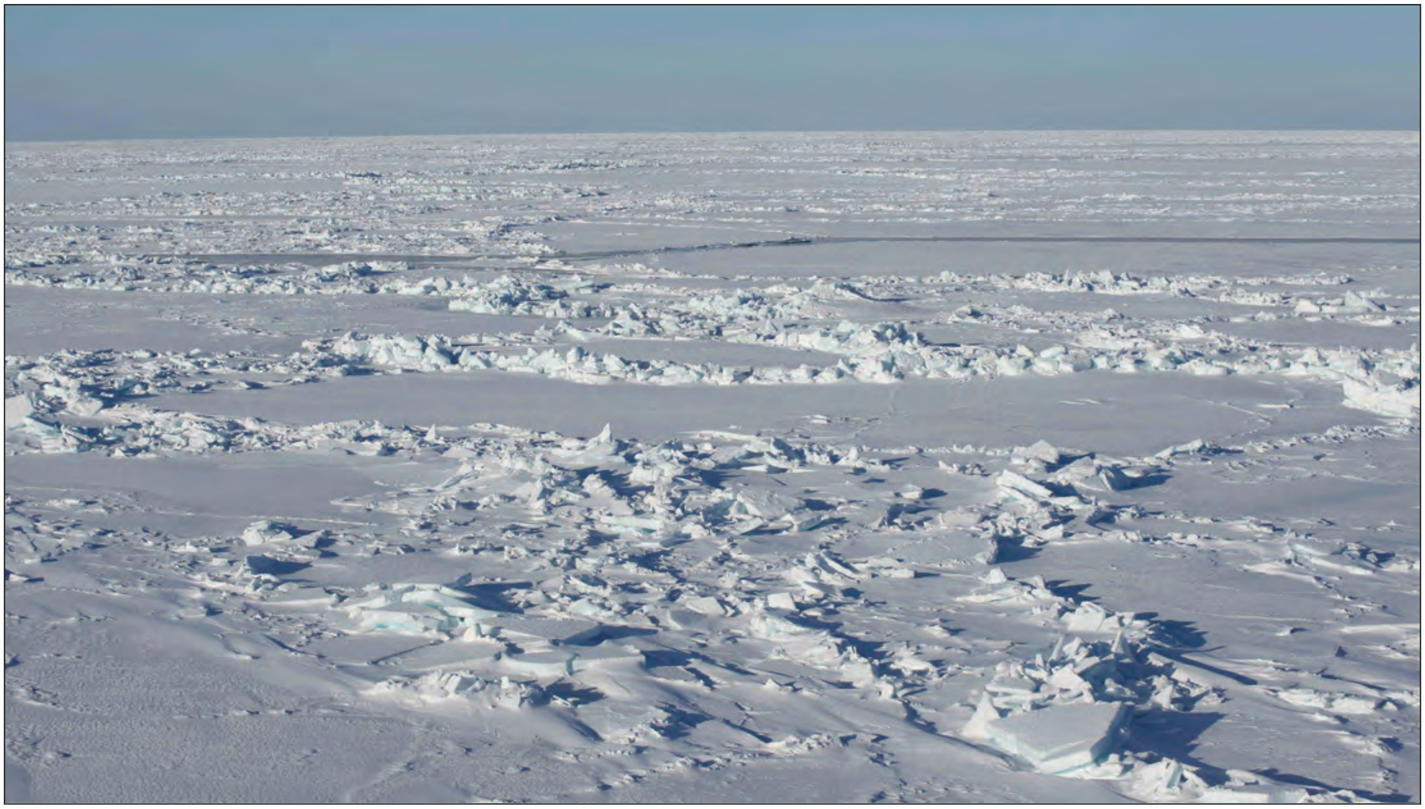


Vertical distribution of ice algal pigments in an ice floe collected in the Bering Sea. The ice was 50 cm thick, and the highest algal pigment concentrations occurred in the bottom 2 cm of the ice floe. Water column phytoplankton concentrations at the same locations were two orders of magnitude lower.

The Big Picture

The Bering Sea supports an incredibly rich marine ecosystem with a wealth of marine resources exploited by commercial and subsistence harvests. Change in ocean conditions, including sea ice characteristics, impact the functioning of marine systems. To enable predictions on future scenarios, we need to understand the interplay between the current system components like fish, birds, plankton, sea floor, and sea ice plant and animal life. Our project provides one of the building blocks to understand how the Bering Sea ecosystem functions and how it might change in the future.

Fig. 2



R. Gradinger

Sea ice covering the Bering Sea as seen from an icebreaker in March 2009.

Fig. 3

C. Morel

Taking ice samples with an ice corer.

collecting water from below the sea ice, using a small water sampler deployed through holes in the ice. We also measured when and how those algae melted out of the ice by collecting sinking material with sediment traps under the ice. We used chemical markers to follow the fate of the ice-derived matter in the food web.

Why We Did It

Sea ice is an integral part of Arctic marine ecosystems, serving as breeding and migration ground for marine mammals, resting area for birds and seals, and as a realm for hundreds of different species, from microscopic, unicellular plants to larger animals. Given all the recent changes in temperature and ice conditions in the Bering Sea, the big questions were (1) how important are these sea ice related ecosystems for the Bering Sea food web, (2) how much ice algal biomass is formed during spring prior to the ice melt, and (3) how is the production linked to the water column and seafloor communities.

Rolf Gradinger, University of Alaska Fairbanks (UAF)
Bodil Bluhm, UAF
Katrin Iken, UAF

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Origin and Fate of Nitrogen on the Eastern Bering Sea Shelf

FERTILIZER FOR AN ECOSYSTEM

The Bering Sea shelf is an exceptionally productive ecosystem, owing in large part to high concentrations of nutrients delivered to the shelf from the open Bering Sea. Nutrients entrained seasonally onto the shelf from the slope are thought of as "fertilizer" that leads to prolific spring phytoplankton blooms in marginal ice zones. The concentration of bio-available nutrient nitrogen (N) delivered to the shelf is particularly important, because its concentration in slope waters relative to other nutrients is below the physiological requirement of phytoplankton. The Bering Sea shelf is consequently a nitrogen-limited system, whose fertility is dependent on the amount of nitrogen fertilizer in shelf waters.

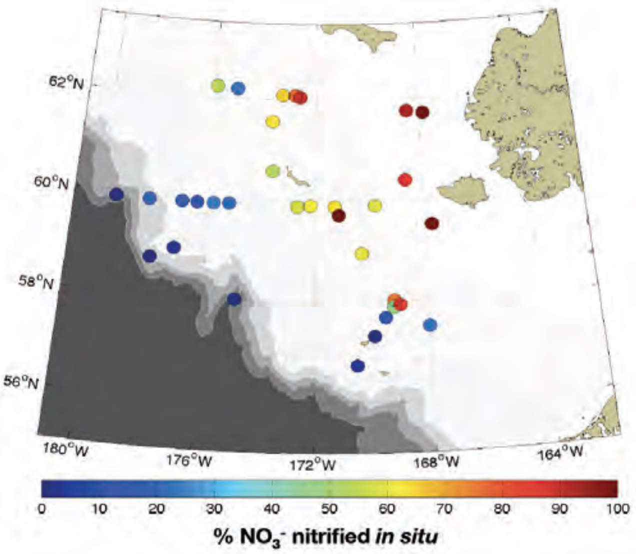
How We Did It

We investigated the origin of nitrogen and its cycling on the shelf from measurements of nutrient concentrations (specifically nitrate, nitrite, ammonia, and phosphate) and from corresponding measurements of the natural abundance stable isotope ratios ($^{15}N/^{14}N$) of discrete nitrogen pools in early spring shelf waters of 2007 and 2008 on the ice-covered shelf. By examining the stable isotope ratio measurements of the different types of samples in relation to each other, we were able to start building a picture of the movement and transformations of nitrogen through the shelf water, sediment, and organisms.

Our observations revealed that, as expected, the annual resupply of nutrient N, in the form of nitrate, from the open Bering Sea contributes an important fraction of the

continued on page 2

Fig. 1



The proportion of nutrient nitrate originating from the decomposition of shelf material rather than newly imported in waters from the slope, relative to the total nitrate.

The Big Picture

Given sufficient light and adequate nutrients, phytoplankton will thrive. The seasonal retreat of sea ice on the Bering shelf allows for sunlight to penetrate the sea surface, and phytoplankton begin to bloom in nutrient-rich waters. The size of the blooms is ultimately determined by the concentrations of nutrient nitrogen in the water, which occurs in lower concentration relative to other plant nutrients. We sought to determine the amount of nutrient N replenished seasonally to the shelf from the slope, and monitor the fate of this N once on the shelf. Our conclusions: Nitrogen sourced from decomposition in sediment is a dominant source of nutrient N for the spring bloom, increasingly so inshore.

NITROGEN SUPPLY FOR NEW PRODUCTION AND ITS RELATIONSHIP TO CLIMATIC CONDITIONS ON THE EASTERN BERING SEA SHELF
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

"fertilizer" available for the spring bloom upon ice retreat, particularly so on the outer shelf and on the seaward portion of the middle shelf. Shoreward on the middle and inner shelf, however, nearly all of the N in the water column originates from mineralization *in situ* (Figure 1). Through this process, organic material accrued in sediments from the previous season's growth is decomposed in sediments during the dark winter, and released as inorganic nutrients back to the water column. In this way, the shallow continental shelf recycles and retains nutrients through the winter, and re-mobilizes these to the water column, thus fertilizing the spring bloom.

Why We Did It

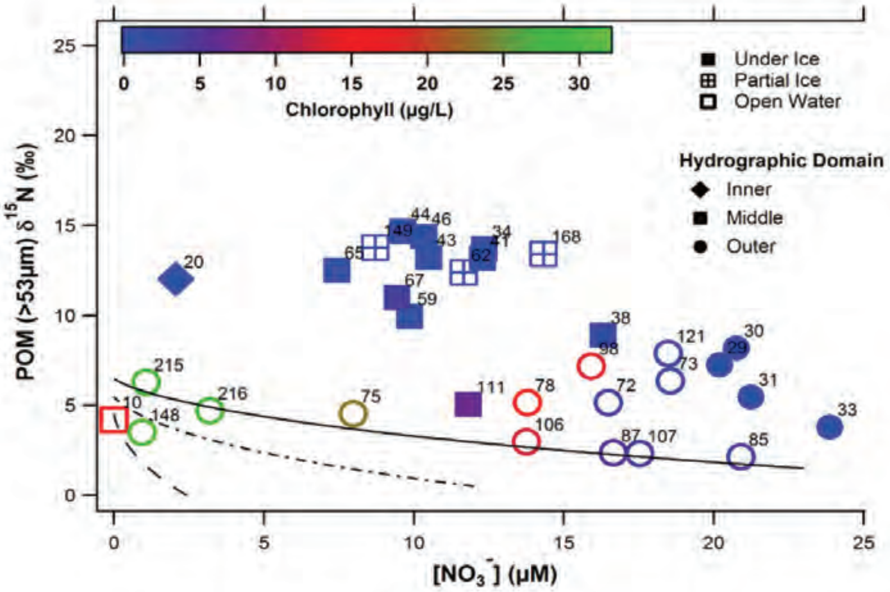
The concentration of N fertilizer relative to phosphorus, another nutrient, decreases dramatically inshore and northward, because bioavailable N is converted to unavailable N_2 gas by denitrifying bacteria in sediment. So-called "denitrifiers" actually "breathe" nitrate when oxygen runs out in order to decompose organic material. This is paradoxical, in a sense, because the more fertile the shelf as a result of the amount of nitrogen fertilizer in the water, the more this bioavailable nitrogen gets used up during the decomposition of dead algal material by denitrifying bacteria in sediments. This removes the nitrogen fertilizer from sediments and from water above the sediments, converting this usable nitrate into unusable N_2 gas! This conundrum motivates our research, to try to understand how much fertilizer N is "breathed" to unusable N_2 gas during decomposition in sediments rather than re-released to the water column to fertilize subsequent algal blooms.

We also found that phytoplankton and their predators had a much higher $\delta^{15}N$, the $^{15}N/^{14}N$ ratio, in the ice-covered portions of the shelf than those from areas of open water (Fig. 2). Algae growing under sea ice obtained nitrogen in the form of ammonium rather than nitrate, which gave them a distinctively higher $\delta^{15}N$ than open-water algae. Zooplankton feeding on ice-associated algae similarly adopted a higher $\delta^{15}N$ than those feeding on open-water algae. Because this distinct spatial pattern in the $\delta^{15}N$ of algae is transferred to their predators, it may prove useful for tracing the diet and movements of animals on and off the ice-covered shelf.

Julie Granger, Department of Marine Sciences, University of Connecticut
Maria G. Prokopenko, Geology Department, Pomona College
Laura V. Morales, Department of Plant Sciences, UC Davis
Daniel M. Sigman, Department of Geosciences, Princeton University

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Project and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



$^{15}N/^{14}N$ ratio ($\delta^{15}N$) of POM (Particulate Organic Material = algal material) in the water column of the Bering Sea shelf vs. nitrate concentration, in relation to relative sea ice cover. Phytoplanktonic algae growing under sea ice have a distinctively greater $\delta^{15}N$ than open-water algae. Numbers correspond to those of individual shelf stations. Lines delineate the expected $^{15}N/^{14}N$ of POM derived solely from the partial assimilation of nitrate at the inner, middle and outer shelf.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

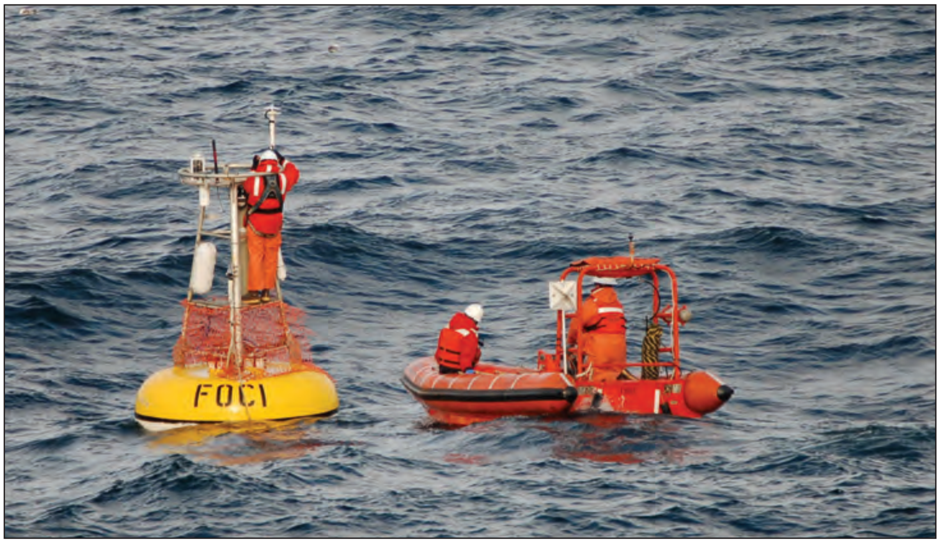
Biophysical Moorings

TAKING MOTHER OCEAN'S PULSE FROM AFAR

The Bering Sea shelf is a big place. It is bigger than the state of California, with weather that challenges even the saltiest seafarers. Ships provide the best platform for scientists to make most ocean measurements, but both funding and seasonal ice cover limit ship-based research in the Bering Sea. Scientists with the joint research program Ecosystems & Fisheries-Oceanography Coordinated Investigations (EcoFOCI), have used moored oceanographic instruments ("moorings"), like a stethoscope anchored to the seafloor, to track the health of the Bering Sea year-round since 1995. These moorings provide decades-long records of important ecosystem variables.

During the Bering Sea Project we discovered that water is less sharply stratified in the north than the south because tides are weaker. This creates a stable layer above the bottom mixed layer and below the surface mixed layer, which receives sufficient light to support a sub-surface phytoplankton bloom in the north during summer. Summer primary production can affect the productivity of the entire food web. We discovered how the spring phytoplankton bloom is affected by ice retreat, and that blooms occur deeper below the surface in the

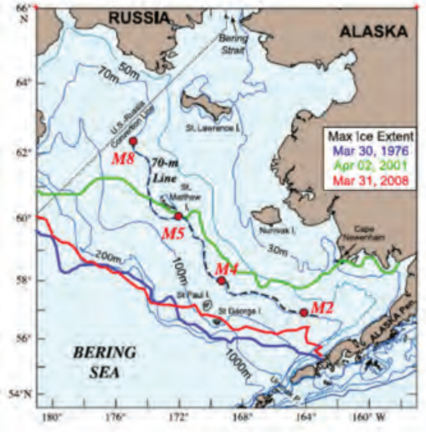
continued on page 2



Edward Cokelet

EcoFOCI scientist Scott McKeever removes sensitive equipment on the surface buoy of the M2 Mooring before bringing it onboard the ship.

Fig. 1



EcoFOCI maintains an array of four moorings on the southeastern Bering Sea Shelf (M2, M4, M5, M8). M2 began the 19th year of observation in 2013.

The Big Picture

Long-term biophysical moorings provide year-round measurements of the state of the Bering Sea, filling the gaps in knowledge between ship-based observations. These measurements provide a foundation for understanding the mechanisms that drive this productive region. The Bering Sea Project provided the opportunity to look at targeted ecosystem questions about the physical, chemical, and biological changes in climate and ocean conditions in the context of this long-term data set. During the Bering Sea Project, we used data from these moorings to help answer questions about the differences between the northern and southern Bering Sea, and if animals will be able to shift their ranges northward with climate warming; the difference between warm and cold years on the Bering Sea shelf and how the animals that live here are affected; and how the timing of the spring bloom will affect everything from the smallest plankton to the largest whales.

north. We learned that the magnitudes of the spring and fall blooms are related, and that the interval between blooms can vary by up to two months. This length of time between spring and fall blooms may affect the amount of production (i.e., food) that reaches higher trophic levels, including fish, seabirds, and whales.

How We Did It

EcoFOCI maintains an array of four long-term biophysical moorings in the Bering Sea (Figure 1). Each mooring hosts instruments that make hourly measurements of temperature, salinity, nitrate, chlorophyll (fluorescence), currents, and sea ice, year-round (Figure 2). The instruments are programmed to take measurements at least every hour and then store the data. The M2 mooring also hosts acoustic instruments that record zooplankton size and abundance and marine mammal vocalizations. Moorings are recovered and re-deployed using ships in spring and fall, weather and ice permitting.

Why We Did It

The Bering Sea supports abundant and diverse wildlife, coastal communities, and some of the world's most commercially valuable fisheries. This cold, shallow sea is also extremely variable, so predicting changes in ocean conditions has great value from economic, ecological, and public safety perspectives. We continue to measure the vital signs of the Bering Sea to better understand how this ecosystem responds to change. The Bering Sea oscillates between periods of relative warm and cold conditions (Figure 3). Observing how the ecosystem responds to warm periods (i.e., 2000-2005) vs. cold periods (i.e., 2006-2010) can help us predict how this ecosystem responds to climate warming. This information will help us adapt to a changing climate and ensure that the living marine resources of the Bering Sea continue to be managed in a sustainable way.

Lisa Sheffield Guy, University of Washington Joint Institute for the Study of the Atmosphere and Ocean

Phyllis J. Stabeno, National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory

Jeffrey Napp, NOAA Alaska Fisheries Science Center

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Project and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2

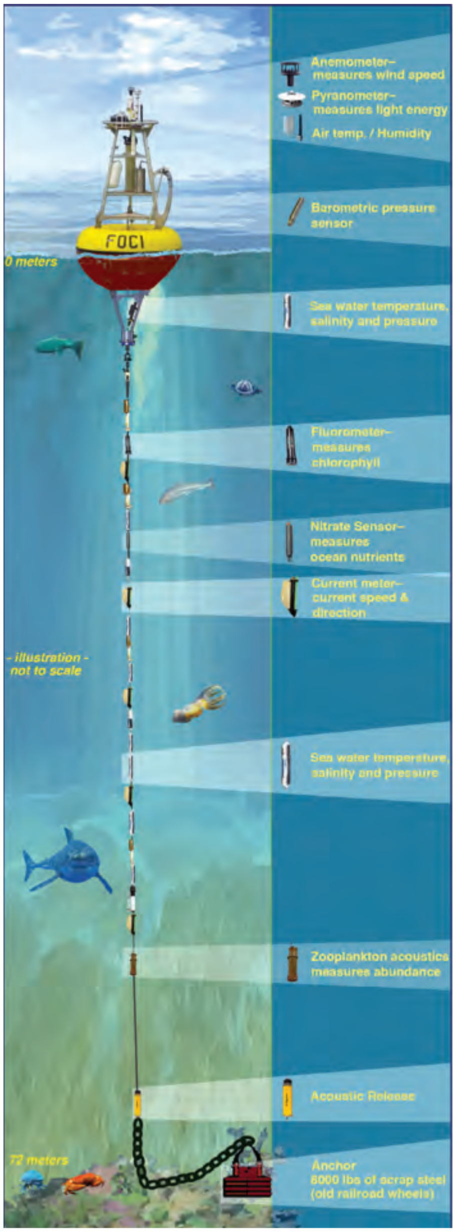
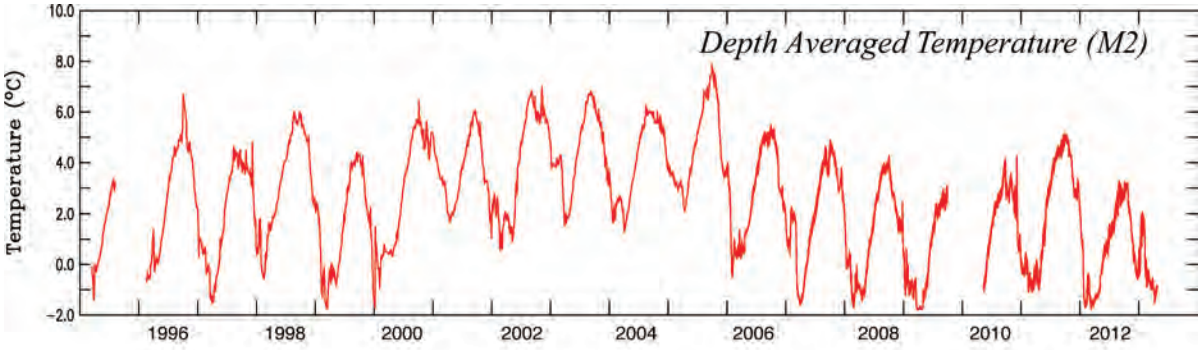


Diagram of a biophysical mooring including surface buoy (ice-free seasons), illustrating how instruments are arranged along the length of the mooring.

Fig. 3



Temperature averaged across all depths measured by the M2 mooring during 1995-2011.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

North-South Differences in the Eastern Bering Sea Shelf

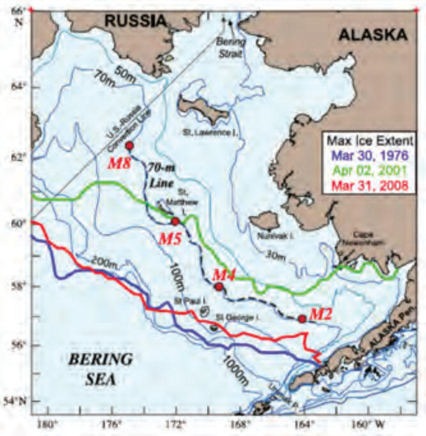
CHANGES IN LATITUDE; CHANGES IN ATTITUDE

In the ocean, hard physical borders do not exist. So what environmental cues tell organisms when they are in a suitable habitat? One feature, which splits the Bering Sea middle shelf in two and forms a transitional line between the northern and southern Bering Sea, is defined by seasonal sea ice and water temperature. We discovered that this line, found between 59° and 61° latitude, is essentially the divide between the cold north, where salt and temperature both play a role in vertical stratification, and the warmer, more sharply stratified southern shelf. This boundary persists through the summer, but may become more diffuse due to the horizontal transport of water onto the shelf.

We observed that the presence or absence of seasonal ice affected the strength and location of the boundary, along with water characteristics such as currents and temperature on either side. The southern shelf was sharply stratified by temperature during summer into warm upper and cooler bottom layers, while the northern shelf had a more gradual change in temperature and salinity. The southern shelf was also much warmer in years without seasonal ice cover. We explored the temperature preferences of Bering Sea fish and snow crab to help predict who the "winners" and "losers" might be in a warmer climate without seasonal sea ice. We discovered that some fish, such as pollock, which

continued on page 2

Fig. 1



Annual ice extent and mooring locations in the eastern Bering Sea. Mooring locations are indicated with the red dot (•) and the north-south transect by the broken line (---). Scientists took measurements in the spring and late summer at the 50+ stations along the transect line. Also shown is the maximum ice extent in three different years; 1976 and 2008 were cold years with lots of sea ice, 2001 was a warm year with minimal ice penetration into the southeastern Bering Sea.

The Big Picture

As the climate changes, water temperatures on the northern shelf will likely remain cold during spring and summer due to seasonal sea-ice cover and darkness, making a simple northward shift in the distribution of Bering Sea species unlikely. However, if the global climate continues to warm, the southern shelf will have less ice, though large interannual variation in ice cover is expected. Biological responses to climate warming could include greater north–south differences in zooplankton communities, the transport of some large zooplankton from the outer to the middle shelf, and the disappearance of two important zooplankton prey (large copepods and krill) for planktivorous fish, seabirds, and whales. The response of commercially and ecologically important fish species is predicted to vary. Some species of fish, such as juvenile sockeye salmon, may expand their summer range into the northern Bering Sea; some (e.g., pink salmon) may increase in abundance, while still other species (e.g., walleye pollock and arrowtooth flounder) are unlikely to become common in the north. Warming of the southern shelf will likely make it more hospitable for subarctic species, but Arctic species, such as snow crab, will be restricted to colder northern waters. Baleen whales will likely be able to extend their range to follow their prey (krill and small fishes) into new areas.

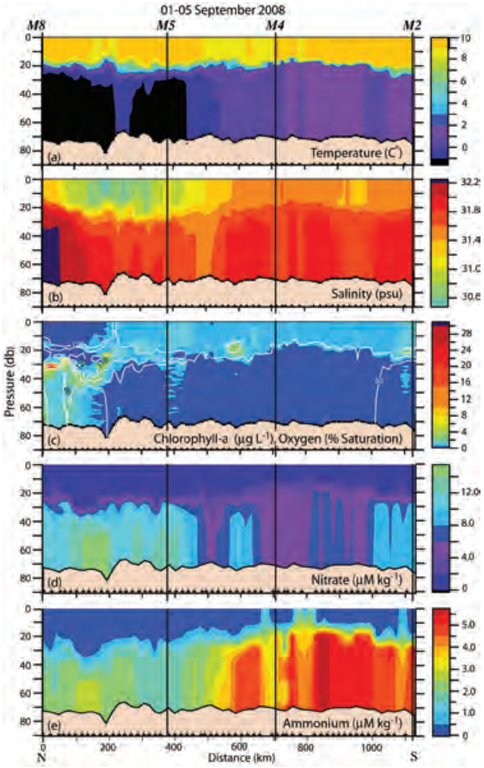
BIOPHYSICAL MOORINGS
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

avoid the coldest waters, could not shift their ranges northward, while others, such as pink salmon, may adapt more easily.

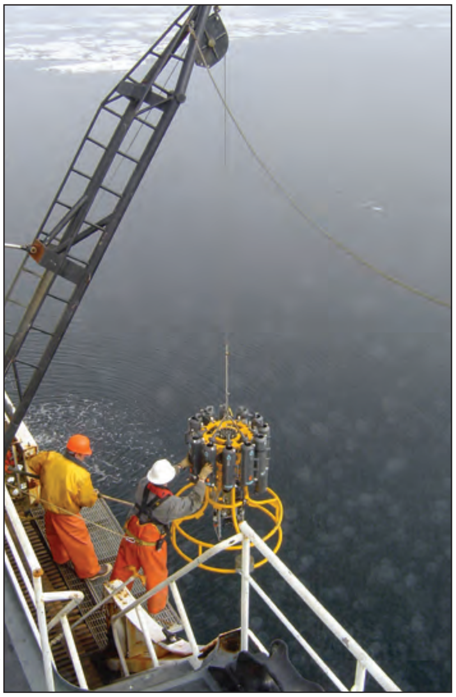
How We Did It

We used sea ice data from moorings and satellites, and data from ships occupying a north-south transect between St. Lawrence Island and Bristol Bay, Alaska. EcoFOCI (Ecosystems & Fisheries-Oceanography Coordinated Investigations), a joint research program between the Alaska Fisheries Science Center and the Pacific Marine Environmental Laboratory, maintains an array of four long-term biophysical moorings in the Bering Sea (Figure 1). Each mooring hosts instruments that make hourly measurements of temperature, salinity, nitrate, chlorophyll (fluorescence), currents, and marine mammal vocalizations, year-round. The M2 mooring also hosts acoustic instruments that record zooplankton size and abundance. Water column measurements of temperature, salinity, oxygen, nutrients and zooplankton were also collected from ship-based surveys (Figure 2). Fish and crab data were obtained from the Alaska Fisheries Science Center trawl surveys (Groundfish Assessment Program, Resource Assessment and Conservation Engineering Division). Whale data were from both visual surveys and moored and shipboard acoustics.

Fig. 2



Results from the north-south transect line sampled in September 2008. Shown from top to bottom: temperature, salinity, chlorophyll-a, nitrate, and ammonium. The four vertical lines through each panel indicate the positions of the four moorings. Note the strong break in temperature and salinity near mooring M5 at roughly 60 N. This is the feature that separates the northern and southern portions of the eastern Bering Sea.



Lindsey Wright

Casting the CTD (conductivity, temperature, and depth instrument) in a sea of ice and jellyfish aboard the NOAA Ship Miller Freeman.

Why We Did It

The Bering Sea supports abundant and diverse wildlife and some of the world's most commercially valuable fisheries. Predicting how these animals will respond to changing conditions will help coastal communities, subsistence users, and commercial fishers prepare for a changing Bering Sea. We wanted to understand if some species would simply move north as seasonal sea ice declines, and which species might be most vulnerable in a rapidly changing ecosystem.

Lisa Sheffield Guy, University of Washington Joint Institute for the Study of the Atmosphere and Ocean

Phyllis J. Stabeno, National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory

Jeffrey Napp, NOAA Alaska Fisheries Science Center

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Project and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Jeffrey Napp

EcoFOCI Scientists Nancy Kachel and Carol Ladd deploy a bongo net aboard the R/V Thomas G. Thompson.

BEST-BSIERP Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Bering Sea Krill and the Impact of Climate Change

SOME LIKE THEIR ALGAE ON ICE

We often hear about decreases in ice coverage and thickness in polar regions, and we can see how climate change is affecting large organisms, like polar bears, but it also affects organisms toward the bottom of the food chain. Euphausiids, more commonly known as krill, are large shrimp-like zooplankton (Figure 1) that are an important food source for larger organisms, including fish, seals, seabirds, and baleen whales. In the eastern Bering Sea, ice typically covers much of the wide shelf in late winter through spring. In early spring, intense blooms of ice algae form in and on the bottom of the ice. There are also algae that thrive in the water (phytoplankton), but they are present in low amounts when there is ice cover and begin to bloom only later, after the ice retreats. We wanted to determine the importance of ice algae in the krill diet and the possible effects of an ice-free springtime on krill.

How We Did It

We worked primarily at night, when krill migrate to the surface water. Krill were captured with a bongo net (Figure 2) that was towed behind our research vessel, and then incubated in water containing the natural community of plankton from the same location. During the incubations, light levels were adjusted to simulate the light exposure to which the krill were acclimated.

To examine the krill's eating habits, we measured the abundance and type of plankton—including ice algae, phytoplankton, and the very small microzooplankton (protozoa)—before and after krill were allowed to feed. We were able

Fig. 1

Krill species Thysanoessa inermis *and* T. longipes, *separated from a bongo net tow collection taken on the outer shelf of the southeastern Bering Sea.*

continued on page 2

The Big Picture

Based on long-term observations, we know that krill are more successful in cold years, when there is lots of ice, than in warm years. It is possible that the earlier-blooming, possibly more nutritious, ice algae kick-start and bolster krill growth and reproduction. If ice cover and extent diminish in the Bering Sea in the future, some species of krill may be less productive, while other species that are not as dependent on ice algae as a food source may be less affected.

THE TROPHIC ROLE OF EUPHAUSIIDS IN THE EASTERN BERING SEA: ECOSYSTEM RESPONSES TO CHANGING SEA-ICE CONDITIONS
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

to determine what they ate, how much, and whether or not they preferred one type of plankton over another. We also analyzed the lipid (fat) profiles in both natural water samples and in the krill themselves before and after feeding. Different types of plankton have different distributions of lipid structures. These can be used to track specific groups of plankton, such as ice algae, through the food chain. Finding these compounds in krill tells us what was eaten and stored in their bodies. The total lipid amount is an important source of calories for those that eat them.

Through a series of shipboard incubations, we were able to analyze changes in plankton concentration before and after krill grazing. We have seen that some krill—*Thysanoessa raschii*, in particular—rely heavily on ice algae as a food source, and the chemical signatures of the ice algae are seen as increased lipids within the krill. The more oceanic counterpart of *T. raschii*, namely *T. inermis*, rely more on planktonic algae and microzooplankton. Changes in sea ice extent and duration in the Bering Sea, with consequent changes in ice algae availability and concentration, may affect the reproductive success of the regional *T. raschii* population to a greater extent than *T. inermis*.

Plankton samples were collected and taken to the lab, where the different quantities and types of plankton were counted. Subsamples of the water collected for incubation were analyzed for lipid biomarkers. At the end of each experiment, the krill were frozen and brought to the lab, along with samples of the plankton collected on filters for biochemical analysis.

Fig. 2

Bongo net deployment at dusk during a summer research cruise.

Why We Did It

Understanding the impact of climate change on krill in the Bering Sea is important because they are a dietary staple for many organisms in that region and a rich source of calories as lipids. Our feeding experiments showed that the most abundant species of krill, *Thysanoessa raschii*, devoured ice algae, when available, at very high rates, up to five times the rate at which they could consume phytoplankton. After the ice melted back and planktonic algae bloomed in the water column, *T. raschii* fed on planktonic algae and microzooplankton. Not all species of krill are alike, though. *Thysanoessa inermis* typically lives farther offshore than *T. raschii*. In this region of the Bering Sea, ice is not as extensive in late spring as it is inshore, and therefore ice algae are less available. Not surprisingly, we found *T. inermis* fed primarily on planktonic algae and microzooplankton.

H. Rodger Harvey, Old Dominion University (ODU) Ocean, Earth, and Atmospheric Sciences

Evelyn J. Lessard, University of Washington (UW) School of Oceanography

Rachel Pleuthner, ODU Ocean, Earth, and Atmospheric Sciences

Megan Schatz, UW School of Oceanography

Tracy Shaw, Hatfield Marine Science Center, Oregon State University

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Project and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Climate and Bering Sea Fisheries: Beyond a Northward March

SURPRISING IMPACTS ON BERING SEA POLLOCK AND PACIFIC COD FISHERIES

While some other global scale research has suggested that a warming climate will propel marine species northward, our work has demonstrated that for the biggest fisheries in the Bering Sea, this has not occurred as expected. For pollock between 1999 and 2009, the fishery shifted northward in the summer, but this occurred in cold years more than warm years. Similarly, for Pacific cod, a larger cold pool (where bottom water temperatures are below 2°C) in cold years has led to fish being more concentrated in northern areas and consequently to more fishing in those areas (Figure 1).

How We Did It

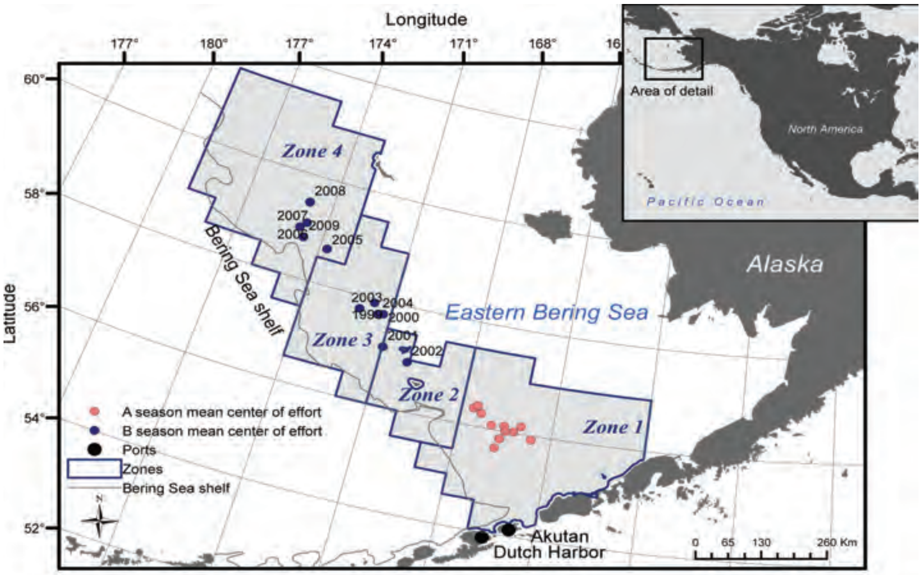
A significant component of our research has been focused on identifying the mechanisms by which climate impacts fisheries. We use data on fishing locations, fish and fuel prices, and how these interact with biological survey information and environmental data. After collecting data and talking to fishermen, we used a variety of statistical methods to see how management, changing prices, and changing biological and environmental measures have impacted the fisheries (Figures 2 and 3).

continued on page 2

The Big Picture

The BEST-BSIERP Bering Sea Project recognized from its outset that humans are an important component of the ecosystem, and that we cannot understand the system without understanding how they use and adapt to the changing environment. By examining the response of largest Bering Sea fisheries to the changing environment, we have illustrated that people will not respond in a simple manner to the changing environment. A better understanding of how the fishery behaves in warm, low-abundance years will help inform how the fishery will react in the future. Managers can use this information to better anticipate how fisheries will interact with other parts of the ecosystem, which can contribute to better-managed fisheries.

Fig. 1



*The Eastern Bering Sea and the fishing areas of the catcher–processor fleet. Points represent the catch-weighted mean center of the distribution of fishing hauls by season. Note the large distinction in the movement of the fishery over time that occurs in the summer fishery B season as well as the lack of movement in the winter fishery A season. [From Haynie, A. and L. Pfeiffer. 2013. "Climatic and economic drivers of the Bering Sea pollock (*Theragra chalcogramma*) fishery: Implications for the future." Canadian Journal of Aquatic and Fisheries Science. 70(6): 841-853, 10.1139/cjfas-2012-0265.]*

SPATIALLY EXPLICIT INTEGRATED MODEL OF POLLOCK AND COD
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

From this research, we have seen that abundance and environmental conditions both directly impact where the fisheries occur. Other BSIERP work has indicated that we are likely to see more low-abundance years with a warming climate (Mueter et al., *ICES* 2011), but in recent times, warm years have also been high-abundance years. As shown in Figure 3 and discussed in the Haynie and Pfeiffer ICES 2012 article referenced in Figure 2, we have not yet experienced a likely future state of warm, low-abundance conditions.

Why We Did It

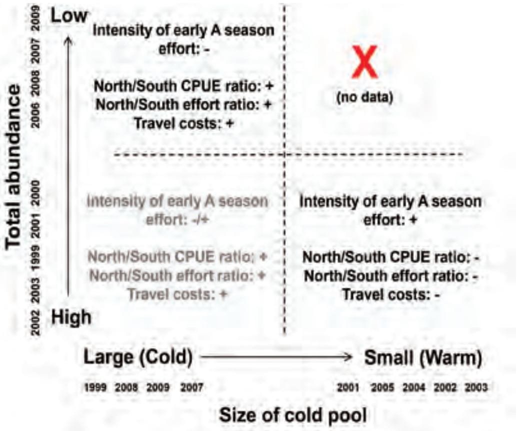
Fishers are the apex predators of the Bering Sea ecosystem, and their spatial behavior can tell us a great deal about the way in which fish populations are shifting under changing climate conditions. After controlling for other factors, how has variation in climate conditions affected the spatial extent of Bering Sea fisheries? How do we expect predicted changes in future climate to impact fisheries and fishing communities? Informing decision-makers on how climate and fisheries are interacting is essential to the effective management of marine resources in the future. The decisions that managers make now will impact the welfare of fishers, communities, the nation, and the ecosystem over the next century.

Alan Haynie, National Oceanic and Atmospheric Administration (NOAA) Fisheries, Alaska Fisheries Science Center (AFSC)

Lisa Pfeiffer, NOAA Fisheries, AFSC

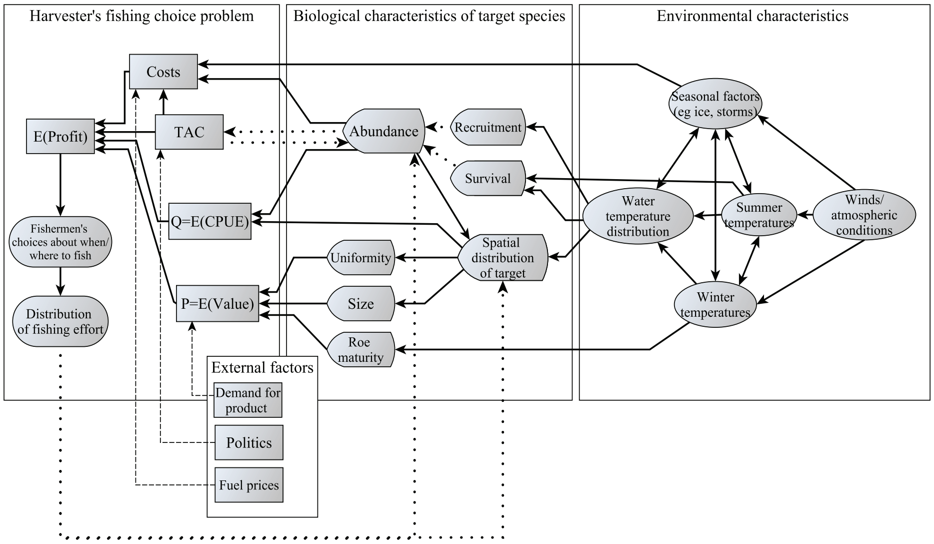
The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 3



Summary of the effects of the size of the cold pool and total pollock abundance on the intensity of early A-season (winter season) effort, B-season (summer season) catch per unit effort (CPUE), B-season effort, and B-season travel costs. Years in the sample characterized by varying abundance and cold pool levels are listed on the horizontal and vertical axes. [Also from Haynie and Pfeiffer CJFAS 2013, referenced above.]

Fig. 2



A conceptual model of how the environment affects the distribution of fishing effort, including the total allowable catch (TAC) and the cost per unit effort (CPUE). Arrows represent the direction of causality, and dotted lines represent mechanisms that may occur on a non-contemporaneous time scale. [From Haynie, A. and L. Pfeiffer. 2012. "Why economics matters for understanding the effects of climate change on fisheries." ICES Journal of Marine Science, 69 (7): 1160-1167, doi:10.1093/icesjms/fss021.]

A catch of pollock on the NOAA ship Miller Freeman, *a fisheries oceanography vessel that works predominantly in the Bering Sea and the North Pacific Ocean.*

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Seasonal Bioenergetics in the Bering Sea

THE FATTER THE BETTER

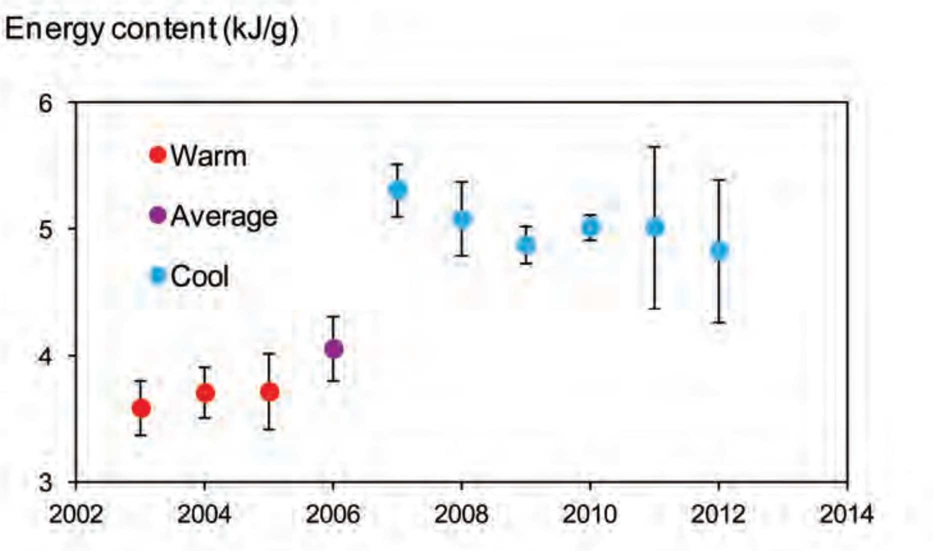
Being fat is good when you have to survive a long winter with very little food to eat. This seems obvious, but it is one of the most interesting and important discoveries we have made from our studies of juvenile pollock in the Bering Sea. Winter is a time when food is scarce for juvenile fish that must use their fat stores to survive. We found that fish that are fat at the beginning of winter survive better than those that are lean. Apparently, the more fat they have the better, because small fat fish do not survive as well as big fat fish. We also realized that fish get big and fat by eating fatty prey, and we found that fatty prey were most abundant when conditions in the Bering Sea were cooler, with longer lasting sea ice, rather than when they are warmer (Figure 1).

How We Did It

Fat fish have more calories per unit weight than lean fish. We used a method called bomb calorimetry to measure the number of calories in a fish. Essentially, we dry the fish, put it in a machine that sets it on fire and then measures how much heat is produced (Figure 2). The amount of heat produced directly reflects its calorie content. We applied this method to samples of fish and their prey collected from the Bering Sea between 2003 and 2010. During this period, the Bering Sea underwent a shift from "warm years" characterized by an early sea ice retreat to "cool years" characterized by late sea ice retreat. When we compared the calorie content of the fish and their prey to these different climatic conditions, we saw fish and their prey were leaner in warmer years than in cooler years. We were also able to

continued on page 2

Fig. 1



This is the amount of energy in a gram of juvenile pollock tissue (measured in kilojoules per gram) in each of the years we have surveyed the Bering Sea. The red symbols show the energy content in warm years and the blue symbols show the cool years. It is clear that the energy content of pollock has changed between warm and cool years.

The Big Picture

We found a similar story for Pacific cod as we did for pollock. This suggests that a warming Bering Sea is likely to produce less protein for us to consume, or that the protein we harvest from the Bering Sea may have to come from new sources. Predicting how climate change will influence the Bering Sea ecosystem was a primary goal of the Bering Sea Project. The observations we made were consistent with an overall picture that the organisms we depend on from the Bering Sea have evolved life history strategies that rely on the presence of ice in spring. As the Bering Sea warms and ice retreats earlier and earlier, juvenile forms of the species we depend on will find it more and more difficult to survive.

A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

compare the total number of calories in the fish to the number of fish that survived and were eventually caught in fisheries. We discovered that the years that produced big and fat juveniles were the same years that produced more fish for the fishery.

Why We Did It

The pollock fishery in the Bering Sea is one of our largest fisheries, and it represents an important source of protein for the country. So understanding how climate affects fisheries can be thought of as a question of food security for our country. We believe that the impacts of climate on fisheries and fish populations are most discernible among juvenile fish because they must use energy to grow and avoid predation or store it to avoid starvation, especially over the winter. Climate has a profound influence on how fish deal with these conflicting demands by influencing the availability and quality of their food, the rate at which they use energy for daily activities, and how much food their predators need.

Ron Heintz, National Oceanic and Atmospheric Administration (NOAA) - Alaska Fisheries Science Center (AFSC), Auke Bay Laboratories

Elizabeth Siddon, NOAA – AFSC, Auke Bay Laboratories

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2

This shows our calorimeter and all the various components. Fish (1) are ground up (2) and dried into a powder (3). A sample of the powder is pressed into a pellet (4) and loaded into the pellet holder (5), which has a fuse installed. The pellet and fuse are loaded into the bomb casing (6) and the casing is filled with oxygen and then placed in the water bath (7). Electrodes heat the fuse, which ignites the powder and generates heat that warms the water bath. A thermometer in the water bath records the change in temperature, and a computer converts the temperature change into calories.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Defining Ecological Regions in the Bering Sea

SYNTHESIS OF PHYSICAL AND BIOLOGICAL DATA TO INFORM SPATIAL MANAGEMENT

Issues of scale are important in understanding competitive and predatory interactions and the influence of external drivers on ecosystem dynamics. Our research evaluated trends in species abundance for evidence of compensation (inverse trends), and synchrony (common trends). The former suggests competition, while the latter suggests an external driver. We also evaluated whether resource partitioning occurs, which would suggest mutual avoidance to reduce competitive interactions.

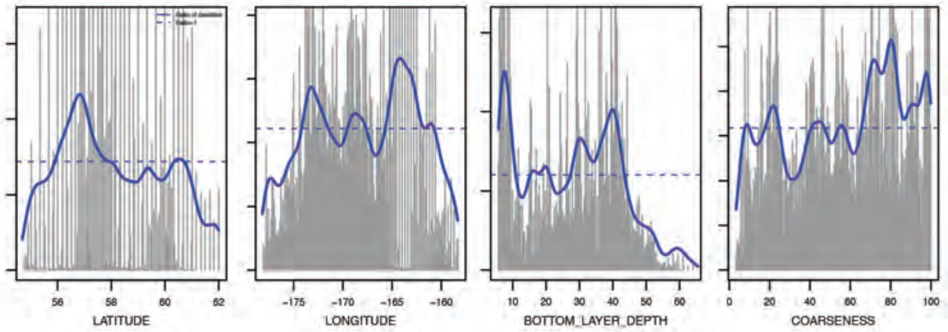
Interpretations of these relationships and trends are strongly influenced by the scale of analysis. To better understand species interactions, community responses to physical drivers, and ecological dynamics at regional scales, we illustrate a statistical approach to delineate distinct ecological regions within large marine ecosystems.

How We Did It

We integrated time-series data on species abundance and the physical environment to better understand factors influencing ecosystem stability and change in the Bering Sea. Using random forest statistical

continued on page 2

Fig. 1



Threshold shifts in the abundance of multiple species along the gradient of select environmental predictors. Gray histograms display the relative importance of environmental values as a breakpoint for shift in distribution for individual species (split values from random forests). Blue lines illustrate a community turnover rate, estimated as the ratio of relative importance and relative density of breakpoints aggregated over individual species (split importance to splits observed). This reflects a rate of change in the aggregate biological community. Peaks above the dashed line indicate locations of greater change in community composition.


Matt Baker

The Big Picture

Effective management of marine resources requires tools to identify structure in ecosystems and better understand processes at regional scales. Our methods delineate ecological regions on the basis of threshold shifts in the composition of biological communities along a suite of physical gradients. Maps that distinguish marine areas with distinct biogeography provide an important tool to better understand ecological processes and to facilitate conservation planning and spatial management. Previous efforts have characterized the eastern Bering Sea according to hydrographic patterns or expert-derived delineations of regional differences. Our results build on this, applying a statistical approach with practical utility for fishery management.

FORAGE DISTRIBUTION AND OCEAN CONDITIONS
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

methods, we quantified the relative importance and marginal effect of physical variables (temperature, depth, substrate and stratification) to species abundance, and identified critical thresholds. We then integrated results for individual species to characterize how the distributions of multiple species shift along the gradients of a suite of environmental variables (Figure 1). We also identified threshold shifts in the composition of the aggregate biological community, and used these to delineate distinct regional boundaries (Figure 2).

Why We Did It

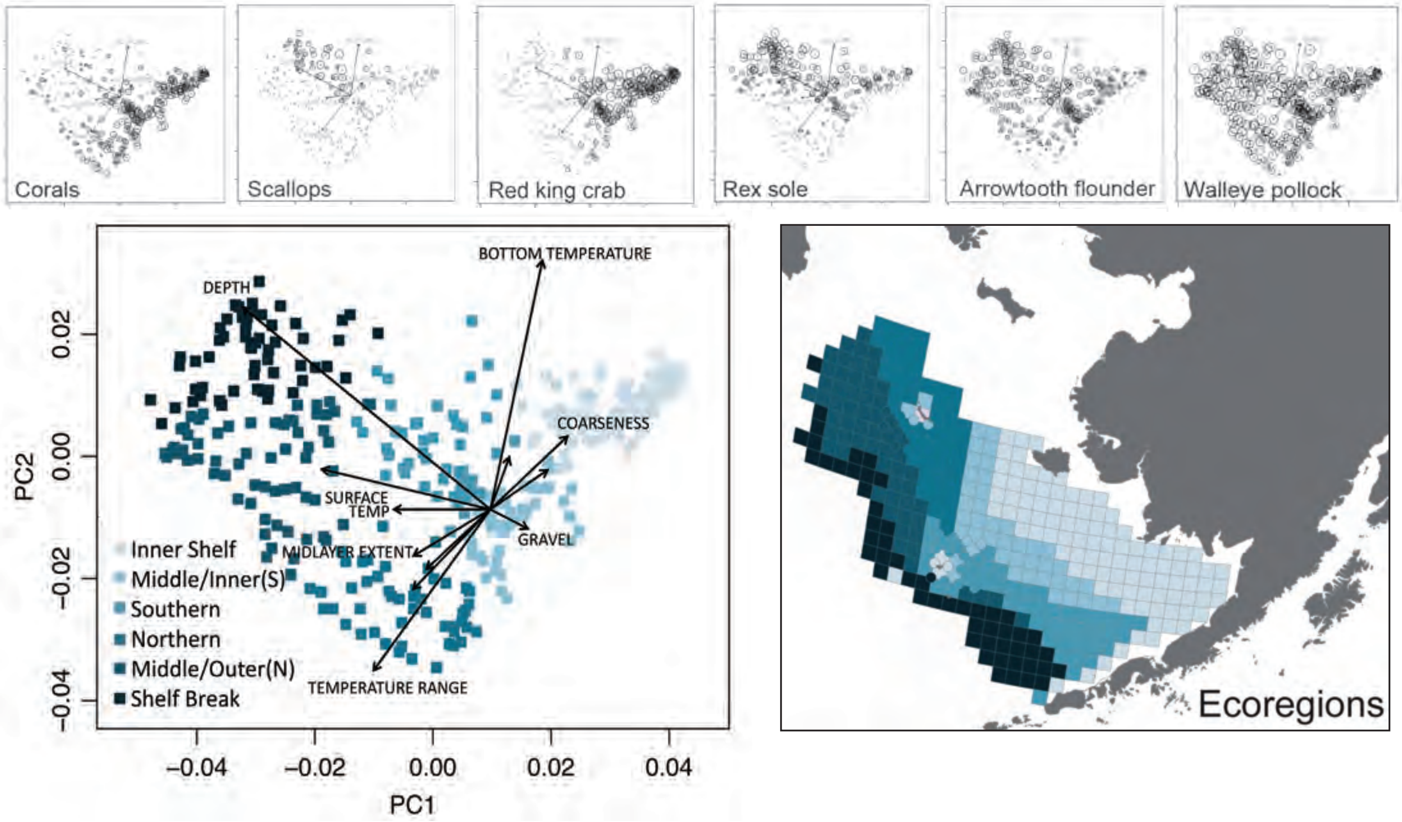
To effectively manage marine resources, we need to understand the relative impact of environmental drivers on biological interactions and processes at multiple scales. We sought to develop a standard approach to identify regional substructure in large marine ecosystems and to inform integrated studies of physical dynamics and biological interactions at smaller scales. Species distribution (i.e., biogeography) and interaction are important drivers of ecosystem function and structure. By identifying environmental thresholds for individual species, we are able to better estimate competitive and predatory interactions in multispecies models. Such analyses may also inform spatial management, the importance of stock structure and the relevance of localized environmental drivers.

Anne Hollowed, NOAA Alaska Fisheries Science Center

Matthew Baker, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington; NOAA Alaska Fisheries Science Center

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



Principal component plots of stations in the bottom trawl survey (left) where coordinate position reflects the inferred biological community associated with environmental predictor gradients (arrows) and color refers to distinct ecoregions. Individual survey stations were grouped via clustering methods to delineate distinct ecological regions in the eastern Bering Sea (right). The top row of plots display weighted species abundance per station for select species, demonstrating how individual species respond to multiple environmental variables.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Climate, Population Dynamics and Predator-Prey Overlap

ARROWTOOTH FLOUNDER VS. JUVENILE POLLOCK

Climate- and human-induced changes in marine ecosystems have detectable impacts on the spatial distributions of fishes. However, less is known about how shifts in distributions might alter predator-prey overlap and the dynamics of prey populations. Our study revealed that population size and ocean temperatures have a synergistic effect on the strength of overlap between arrowtooth flounder (predator) and juvenile pollock (prey) in the eastern Bering Sea. Predicted changes in overlap strength occurred largely as a consequence of flounder movement. This result was expected because the abundance of flounder has increased eight-fold over the past three decades, prompting expansion of their habitat. In addition, flounder and pollock distributions are influenced by water temperatures and the location of the cold pool of subsurface water that forms across the continental shelf with the formation and melting of winter sea-ice (Figure 1). Our findings contribute to the growing evidence that continued increases in flounder abundance combined with warming ocean temperatures could translate into higher predation mortality on juvenile pollock in the eastern Bering Sea.

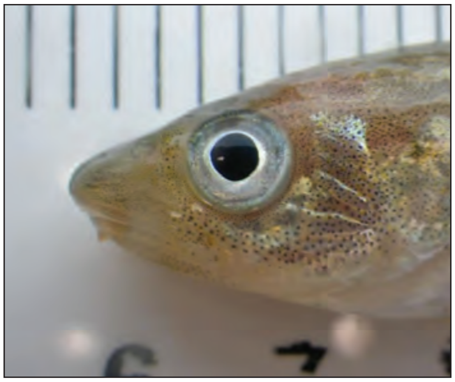
How We Did It

The Bering Sea is an ideal system to examine the ecological consequences of changes in species

continued on page 2

The Big Picture

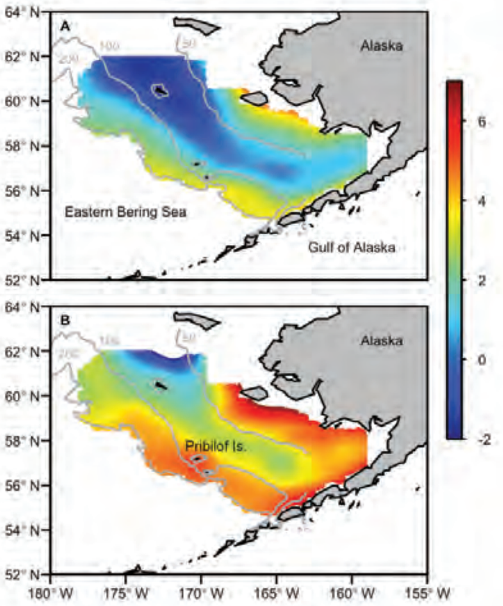
The potential for changes in species distributions and interactions is pronounced in the Bering Sea ecosystem and subarctic systems in general. Not only is climate-induced habitat variability especially strong in these regions, but some of the largest commercial fisheries in the northern hemisphere are found in these waters. Using existing assessment survey data, we examined species abundance, distribution, and interactions to gain insights into predator-prey overlap. Our methodology provides the ability to characterize the dynamics of species interactions and quantify the impact of predators on prey under different scenarios. This methodology is particularly valuable for understanding ecological processes in the Bering Sea, as it improves our ability to anticipate shifts in predator-prey relationships involving key species such as arrowtooth flounder and pollock.



Olav Ormseth

Juvenile pollock.

Fig. 1



Study Region and Cold Pool. *Summer survey bottom temperatures (°C) in the eastern Bering Sea during a cold year (A; 2007) and warm year (B; 2003). The 50 m, 100 m and 200 m depth contours are shown.*

CLIMATE VARIABILITY AND DEMOGRAPHY DICTATE STRENGTH OF PREDATOR-PREY OVERLAP

A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

distribution. Like other heavily harvested systems, the Bering Sea is the focus of intense assessment surveys aimed at estimating species abundance, distribution and predator-prey interactions. The survey data are therefore valuable for improving our understanding of species spatial dynamics and ecological interactions in subarctic ecosystems. Using this data, we first characterized pollock and flounder distribution and then predicted their overlap in relation to further increase of flounder biomass and ocean temperature. We found that the predicted changes in overlap at higher temperatures were greater in years of high flounder biomass (Figure 2a) compared to years of low flounder biomass (Figure 2b).

Why We Did It

Better knowledge of the mechanisms that influence the strength of species overlap can improve our ability to anticipate shifts in predator-prey relationships and forecast ecosystem-level effects of changing environmental conditions. For harvested species, understanding the magnitude and variability of natural mortality can be important for setting realistic harvest goals. Further, the potential impact of the growing flounder population on pollock population dynamics has become a real concern. Alaska pollock provide sustenance for many species of commercial and conservation value, and support the world's second largest single-species commercial fishery. Increased predation by flounder on juvenile stages combined with other top-down and bottom-up pressures on the survival of pollock early life stages could have important ecological and economic consequences.

Mary Hunsicker, College of Earth, Ocean, and Atmospheric Sciences (CEOAS), Oregon State University (OSU)

Lorenzo Ciannelli, CEOAS, OSU

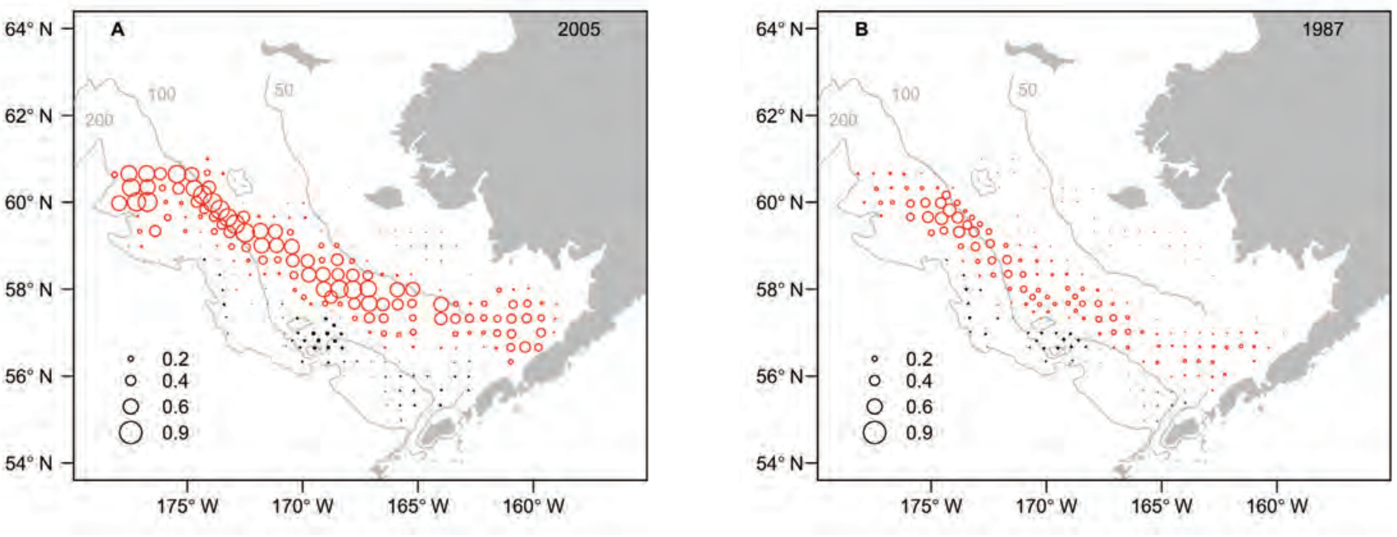
Kevin Bailey, Alaska Fisheries Science Center (AFSC), National Marine Fisheries Service (NMFS)

Stephani Zador, AFSC, NMFS

Leif Christian Stige, Centre for Ecological and Evolutionary Synthesis, University of Oslo

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



Predicted changes in species overlap with increasing temperatures. *Using a a standardized unit increase in spatially-explicit bottom temperatures, red circles indicate locations where the probability of species overlap is predicted to increase, and black circles indicate decrease . The effect of temperature on the magnitude of species overlap was amplified by high flounder biomass. For example, in years when the flounder stock size and temperatures were high (A: 2005), there were large increases in overlap in the northwest shelf and throughout most of the middle and southeast shelf regions. However, when flounder biomass was low (B: 1987), the change in overlap with an increase in temperatures was mostly to the 100 m isobath in the north shelf region. The 50 m, 100 m and 200 m depth contours are shown.*

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Subsistence Food Comes from a Vast Area!

THE BIG PICTURE OF PRODUCTION

Subsistence hunters and fishers are drawing on a vast area of the ocean. Much attention has been given to subsistence use areas, where people hunt and fish. We also looked at the areas of the ocean that help produce those fish and animals. We called this the "calorie-shed," the area that contributes to the food that ends up on people's plates. Using subsistence harvest records to identify important species, we then used biological data to establish how far those species range from the community or area where they are harvested. We did this for Togiak (Figure 1) and Savoonga (Figure 2), using three species for each village. It turns out that the areas are huge!

How We Did It

We began with subsistence harvest records, which told us the species that have the largest harvest by weight. Then we looked at the biological data to identify the species for which good distribution and range data are available. That gave us good information about three important subsistence species in each community. We also had to be specific about the location of interest. For example, when showing the range of the salmon that are harvested in Togiak, we did not want to include the full range of all salmon, but only the range of

continued on page 2

The Big Picture

An issue of great interest to researchers in the Bering Sea Project is how the ecosystem affects people. Analysis of subsistence harvests tells us a great deal about direct human interactions with the ecosystem. Looking at "calorie-sheds," areas of the ocean that produce fish and animals sought for food, gives us another way of understanding how the ecosystem matters to people. In short, coastal residents have a great deal at stake when it comes to ecosystem well-being. This interest extends across the entire region, not just in the areas where people travel, hunt, and fish. Calorie-sheds give us another way of considering how changes in the ecosystem may affect the people who are part of that ecosystem.

Marla Greanya

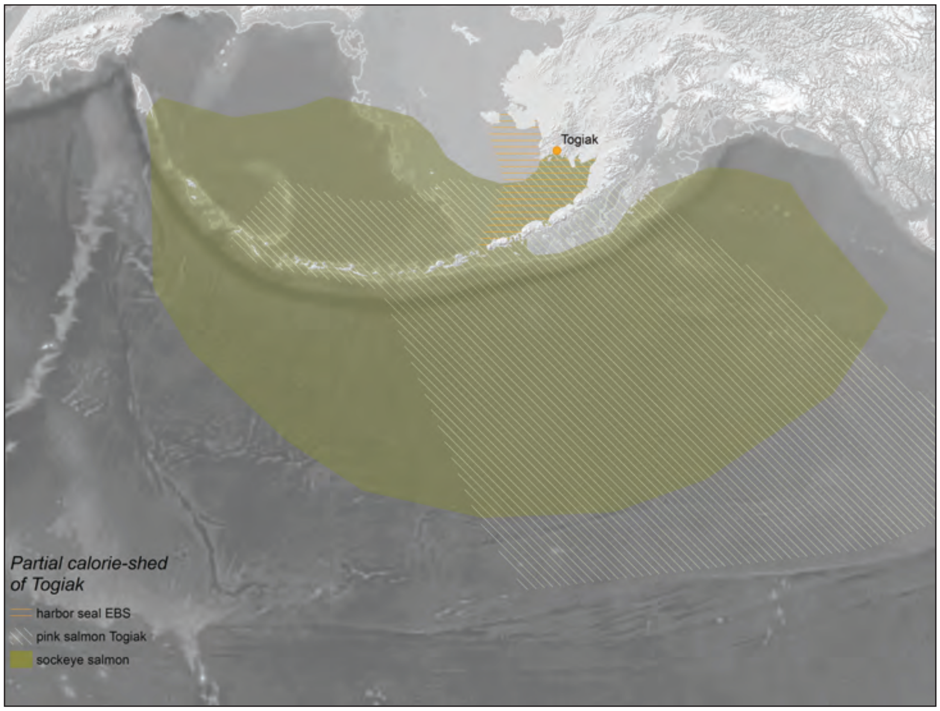
SUBSISTENCE HARVEST AND LTK ECOSYSTEM PERSPECTIVE
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

salmon that return to Togiak, or at least to the Bristol Bay region. Note, too, that these "calorie-sheds" only include the species harvested, not the animals and plants farther down the food web. So, in fact, these are minimum areas.

Why We Did It

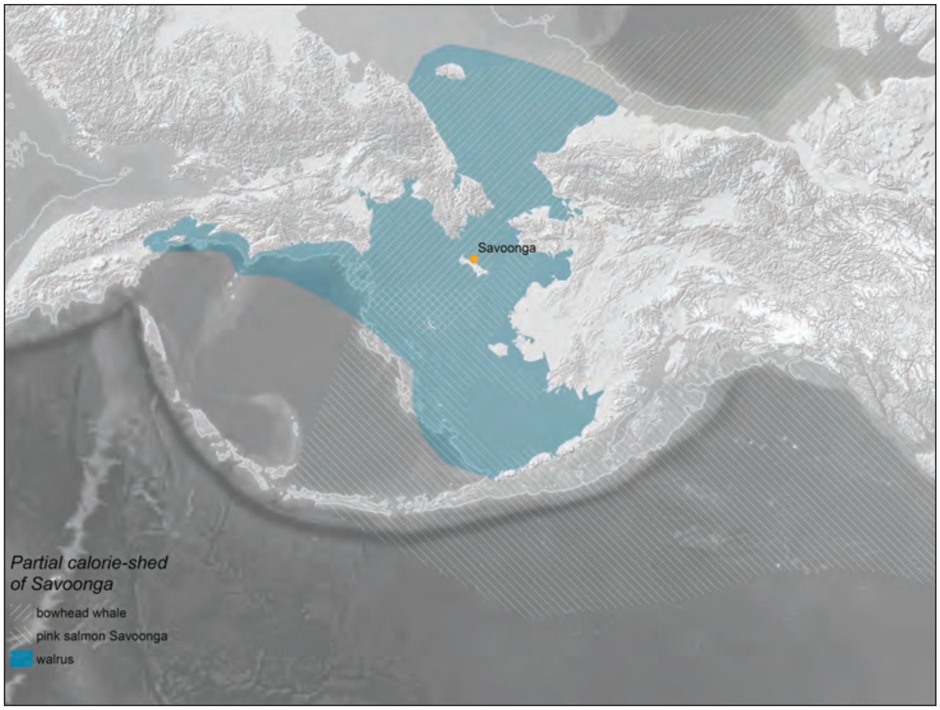
The calorie-shed idea came from wondering about the full geographic extent of people's interactions with the Bering Sea ecosystem. Subsistence use areas show where people go, but there is more to their use of the ecosystem than that. By showing how much of the ecosystem they draw on, we can also show why an individual community might be concerned about what is happening far away. If those distant activities affect the fish, birds, or marine mammals that the community relies on, then they would clearly be interested in what was taking place. In the future, it may also be possible to look at changes in the calorie-shed in light of environmental change, and better understand the implications of change for subsistence communities.

Fig. 1



Calorie-shed for Togiak, based on the distribution of pink salmon, sockeye salmon, and harbor seal.

Fig. 2



Calorie-shed for Savoonga, based on the distribution of bowhead whales, Pacific walrus, and pink salmon.

Henry P. Huntington, Eagle River, Alaska

Ivonne Ortiz, School of Aquatic and Fishery Science, University of Washington

George Noongwook, Savoonga Whaling Captains Association

Maryann Fidel, Aleut International Association & University of Alaska Anchorage (UAA)

Dorothy Childers, Alaska Marine Conservation Council (AMCC)

Muriel Morse, AMCC

Julia Beaty, AMCC

Lilian Alessa, Resilience and Adaptive Management Group (RAM Group), UAA

Andrew Kliskey, RAM Group, UAA

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Local and Traditional Knowledge of the Bering Sea Ecosystem

DETAILS MATTER!

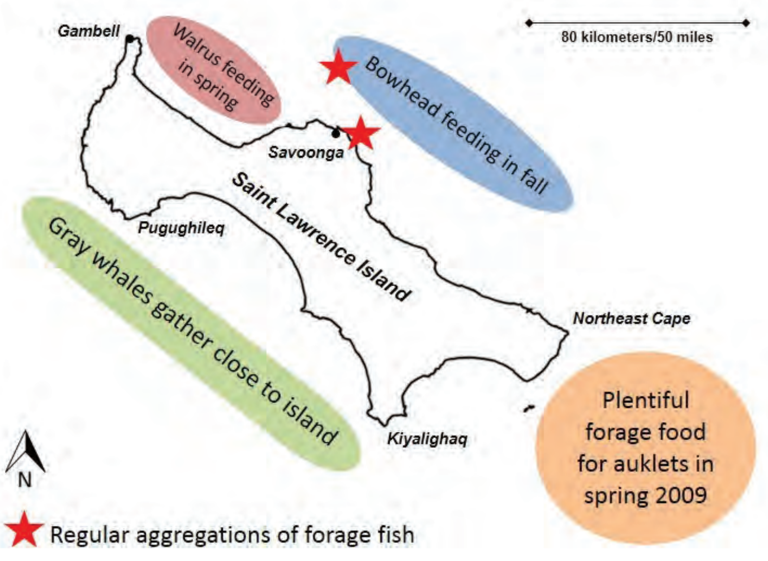
The Bering Sea is a complex and changing ecosystem. In the southeast, many species are in decline. In the north, it remains a productive ecosystem with abundant fish, seabirds, and marine mammals. The most rapid changes are occurring at the edge of the sea ice maximum, in the southern Bering Sea. Ice-associated species, such as bearded seals, are becoming scarce. Ice conditions are also changing in the northern Bering Sea, so we were surprised to find that hunters reported a thriving ecosystem. Of particular interest were descriptions of "hot spots," or areas with very high productivity. Around St. Lawrence Island, hunters noted several such locations, all of which are still productive, attracting an abundance of fish, seabirds, and marine mammals (see Figure 1). Overall, the results from local and traditional knowledge (LTK) are consistent with other findings from the Bering Sea Project.

How We Did It

We interviewed experienced hunters and fishers in five Bering

continued on page 2

Fig. 1



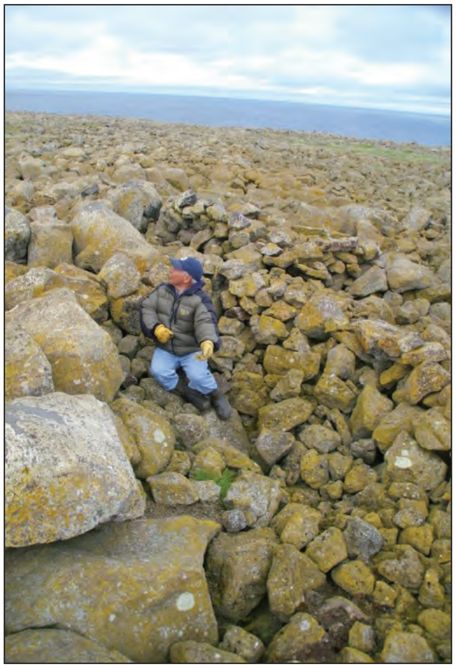
Specific locations associated with particular ecological features/actions in the vicinity of St. Lawrence Island as reported by Savoonga LTK participants.

Caleb Pungowiyi (gray shirt) and Chester Noongwook (red shirt) discuss LTK over a map of St. Lawrence Island.

The Big Picture

In search of local and traditional knowledge (LTK), we interviewed hunters and fishers from several Bering Sea communities. What they shared shed light on several aspects of the Bering Sea Project's research. First, broad differences between the southern and northern Bering Sea had been noted in several other analyses of the ecosystem, and these differences were confirmed with LTK, supporting this interpretation. Second, observations about increased summer storms were contrary to the decrease that was predicted in the Bering Sea Project hypotheses, raising interesting questions for further study. Third, changes in abundance and distribution of species did not follow a simple pattern across the Bering Sea, but showed great local variation, indicating that the ecosystem is complex.

SUBSISTENCE HARVEST, USERS AND LTK ECOSYSTEM PERSPECTIVE
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.



Caleb Pungowiyi demonstrates how to net auklets from an old blind near Savoonga.

Henry Huntington

Caleb Puagowiyi holds a least auklet near Savoonga.

Sea communities: Akutan, St. Paul, Togiak, Emmonak, and Savoonga. We discussed many aspects of the Bering Sea ecosystem, especially those related to the hypotheses driving the entire project. Most of the interviews were open-ended discussions, closer to a conversation than to a poll or a question-and-answer session. After the interviews, we wrote down what we had heard, and reviewed our report with the hunters and others in the communities. Then we made any necessary corrections and other adjustments before sharing the results within our group and with the Bering Sea Project researchers.

Why We Did It

People who live on the shores of the Bering Sea, especially those who spend a lot of time hunting and fishing, have a deep understanding of the environment. In Native villages, this knowledge may have been accumulated over many generations, allowing people to hunt and fish successfully and safely. By documenting what Bering Sea residents know about their ecosystem, we can learn important local details about ecological processes and changes. And we can also check what we have learned from other types of studies by comparing what local residents are seeing with what oceanographers, climatologists, biologists, and others are finding.

Henry P. Huntington

Nicole M. Braem, Alaska Department of Fish and Game (ADFG), Division of Subsistence

Caroline L. Brown, ADFG, Division of Subsistence

Eugene Hunn, University of Washington

Theodore M. Krieg, ADFG, Division of Subsistence

Pamela Lestenkof, Aleut Community of St. Paul Island Tribal Government

George Noongwook, Savoonga Whaling Captains Association

Jennifer Sepez, National Oceanic and Atmospheric Administration (NOAA), (retired)

Michael F. Sigler, NOAA

Francis K. Wiese, North Pacific Research Board, Anchorage

Philip Zavadil, Aleut Community of St. Paul Island Tribal Government

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Changing Wind and Ice Conditions in the Bering Sea

WHEN DO WALRUS HUNTERS CHOOSE TO STAY HOME?

The biggest factor in walrus hunting success is whether hunters go hunting. This is not surprising—but what makes walrus hunters sometimes choose to stay home? Changing wind and ice conditions can affect hunting success, but hunters are used to dealing with variable conditions. We wondered if conditions attributable to climate change may affect walrus hunting by affecting decisions about whether or not to go hunting.

How We Did It

Our analysis considered wind speed, wind direction, and sea ice concentration in relation to walrus hunting from Gambell and Savoonga, on St. Lawrence Island (Figure 1). We used those variables to see how they affected the number of hunting trips that were made and the number of walrus that were harvested.

First we compiled daily data on walrus harvest, number of hunting

continued on page 2

Fig. 1

Map of St. Lawrence Island and the eastern Bering Sea, showing the communities of Gambell and Savoonga.

Marcus Janout

The Big Picture

Bering Sea Project researchers are very interested in how the ecosystem is changing and what those changes mean, especially for people who depend on the Bering Sea for food and for their livelihood. Changes in sea ice are a prominent part of ecosystem change in the region. By examining the impact of changing sea ice, along with winds, we were able to show that walrus hunters on St. Lawrence Island may indeed be affected by those changes, but also that other factors may be more important, such as the skill and experience of the hunters, who are accustomed to dealing with variability and are quick to adjust and adapt as needed.

SUBSISTENCE HARVEST, USERS AND LTK ECOSYSTEM PERSPECTIVE
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

trips, wind speed, wind direction, sea ice concentration, and visibility for both Gambell and Savoonga. Then we analyzed these data using a "generalized additive model." This method allows us to model several parameters together to predict an outcome, so we used wind speed, wind direction, and sea ice concentration at various distances from the villages to see what influence they had, individually and together, on hunting outcomes. We also considered visibility, with the expectation that foggy conditions were not good for hunting, but found that the addition of visibility to the model did not appear to be much of a factor.

One-quarter to one-third of the variability in the number of hunting trips that were made could be explained by wind and ice conditions. While other factors combine to explain much more of the variability, wind and ice conditions do matter. Our analysis also helped explain how they matter, in other words, how a change in wind or ice would affect hunting. For example, higher winds make boating more dangerous and difficult, so hunters tend to stay on shore when it is too windy. Similarly, too much ice makes boat travel difficult, but too little ice can mean there are few walrus since the walrus like to haul out on ice; or too little ice can allow waves to build much higher, again making it dangerous for hunters.

Why We Did It

Hunters in Savoonga told us that wind conditions affect sea ice, and that both together affect how well they are able to hunt walrus. We wanted to test that idea, and also to see if we could understand the relationships between those physical factors and walrus hunting. By doing so, we may be able to understand better how changes in climate can affect walrus hunting.

Henry P. Huntington

George Noongwook, Savoonga Whaling Captains Association

Nicholas A. Bond, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington (UW)

Bradley Benter, Marine Mammals Management, U.S. Fish and Wildlife Service (USFWS)

Jonathan A. Snyder, Marine Mammals Management, USFWS

Jinlun Zhang, Applied Physics Laboratory, UW

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Thomas Van Pelt

George Noongwook leads a discussion of traditional knowledge in Savoonga.

Henry Huntington

George Noongwook driving his skiff along the north shore of St. Lawrence Island, west of Savoonga.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

North to the Arctic

ALBATROSSES INCREASE IN THE BERING SEA

All three species of North Pacific albatrosses are now found in greater abundance and found farther north than in the 1970s–1990s. The increase in sightings of short-tailed albatross (*Phoebastria albatrus*), an endangered species, is good news for conservation—and knowing where they go to forage can help us manage their interactions with fisheries in the future.

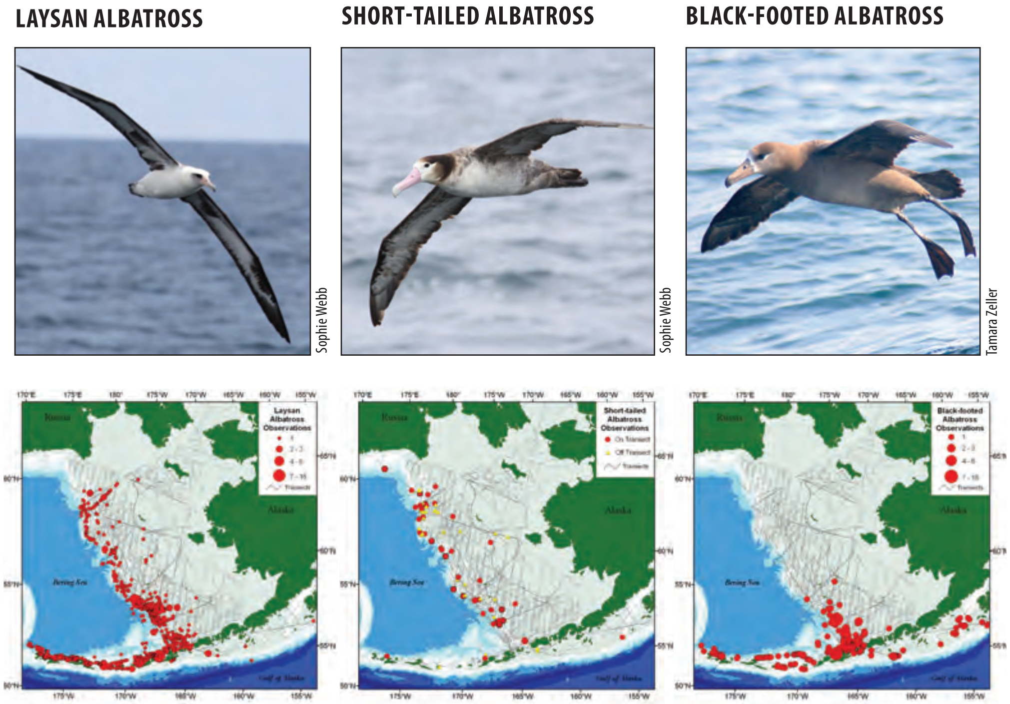
How We Did It

Counting birds at sea from a variety of research vessels has resulted in over 140,000 km of survey transects in Alaskan waters, extending from the 1970s through the 2000s. Work carried out as part of the Bering Sea Project allowed us to extend at-sea surveys in 2008-2010 (Figure 1), and supported examination of decadal changes in seabird distribution (Figure 2). We looked at albatrosses because they are large, conspicuous birds, easy to count at sea, and they are near the northern 'fringe' of their ranges, which makes it relatively easy to notice changes.

Mapping densities of each albatross species over four decades revealed increases and northern expansion in all three species

continued on page 2

Fig. 1



Current distribution of the three albatross species during recent years, primarily during the Bering Sea Project surveys (2008-2010). Red dots are scaled to indicate number of albatross observed; faint gray lines indicate survey effort.

The Big Picture

Albatrosses prefer to forage on squid, which may have increased in the Bering Sea. There is a close overlap in the distribution of albatrosses (Figure 1) and squid (Figure 3) along the Aleutian Islands, the Bering Shelf and near shelf canyons. Additionally, a northward shift in fisheries could draw some vessel-following birds, like albatrosses, farther north. Such broad-scale changes in distribution of an apex predator are indications of ecosystem-level change. By having a better understanding of the changes in albatross distribution, and the mechanisms driving those changes, we can work with commercial fishers to reduce detrimental interactions between albatrosses and fisheries.

SEABIRD BROAD-SCALE DISTRIBUTION
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

(Figure 2). The short-tailed albatross may be reclaiming its former range, since it historically occurred in the Bering Sea and is recovering from near-extinction. But short-tailed albatrosses may even be checking out the Arctic—the first albatross ever recorded in the southern Chukchi Sea (in August, 2012) was a short-tailed albatross. The more common Laysan albatross (*Phoebastria immutabilis*) has also been increasing, especially in the Aleutian Islands, and is now commonly encountered along the entire shelf break. The black-footed albatross (*Phoebastria nigripes*), historically found in the Gulf of Alaska, has increased in the Aleutian Islands, and since the 2000s has been foraging in the southeastern Bering Sea during late summer and fall, when waters are warmest.

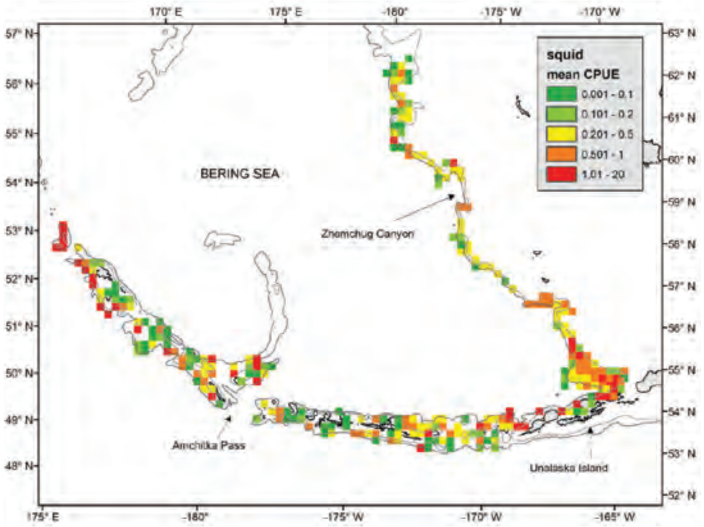
Why We Did It

One of the Bering Sea Project's predictions is that climate change will alter prey distributions, which will ultimately alter distributions of apex predators. The increase in albatrosses in the Bering Sea could be one such example. It could also lead to more interactions with fisheries in the future. The long-term dataset of the North Pacific Pelagic Seabird Database, combined with the Bering Sea Project, has allowed us to look at relative abundance of seabirds over decades.

Kathy J. Kuletz, U.S. Fish and Wildlife Service
Martin Renner, Tern Again Consulting
Elizabeth A. Labunski, U.S. Fish and Wildlife Service
G.L. Hunt Jr., University of Washington
Olav Ormseth, NOAA Alaska Fisheries Science Center

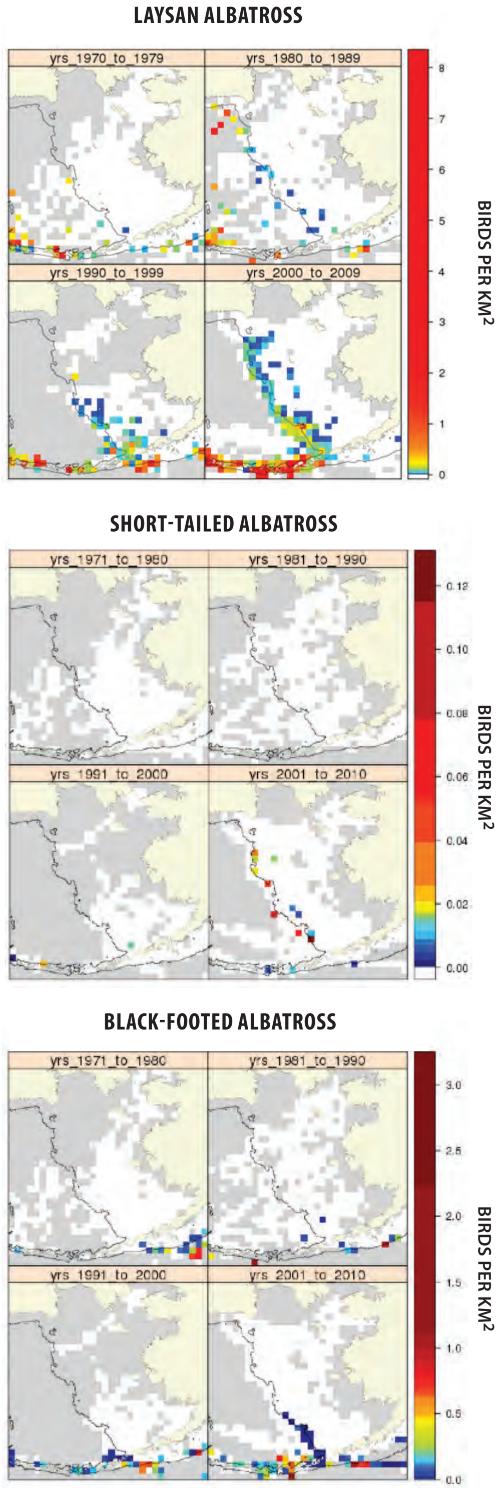
The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 3



Assessment of the squid stock complex in the Bering Sea and Aleutian Islands. Mean Catch Per Unit Effort (CPUE) of all squid species taken in NOAA trawl surveys, 2000-2012, in 20 x 20 km cells.

Fig. 2



Decadal changes in density for the three albatross species found in Alaska. The 1970s, 1980s, 1990s, and 2000s are shown in each of the four small panels, with data binned into 50 x 50 km cells. White cells indicate where surveys were conducted but no birds were recorded on transect.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Climate Change Could Stress Kittiwakes and Other Seabirds

MODELING TO UNDERSTAND LIMITS IN ADAPTIVE BEHAVIOR

For black-legged kittiwakes (*Rissa tridactyla*), mortality increases with increasing levels of stress hormones, and strong relationships exist between indices of environmental variation and stress hormones. These relationships indicate that anticipated climate warming might bring at least short-term demographic benefits for kittiwakes in the Bering shelf region, while having negative impacts on birds breeding in the Gulf of Alaska and western Aleutians. Thus, climate variability is likely to affect survival of North Pacific kittiwakes on a region-specific basis, and the longevity of these birds may not always be sufficient to buffer their populations from low reproductive performance.

What We Found

Using our collaborators' experimental manipulation of food availability during early development, we discovered first breeding at younger ages for kittiwakes that experienced suboptimal natal conditions, as well as greater productivity of early recruiting kittiwakes growing in control nests compared with those that grew in food-supplemented nests. Modeling results further showed that in some colonies it appears birds sacrificed more lifetime reproductive success than a prudent parent would, and that less food early in life led to first breeding at a younger age, as well as greater reproductive effort, compared to birds reared with more food.

Although we found a positive correlation between warmer ocean waters and higher productivity for

continued on page 2


Chris Barger

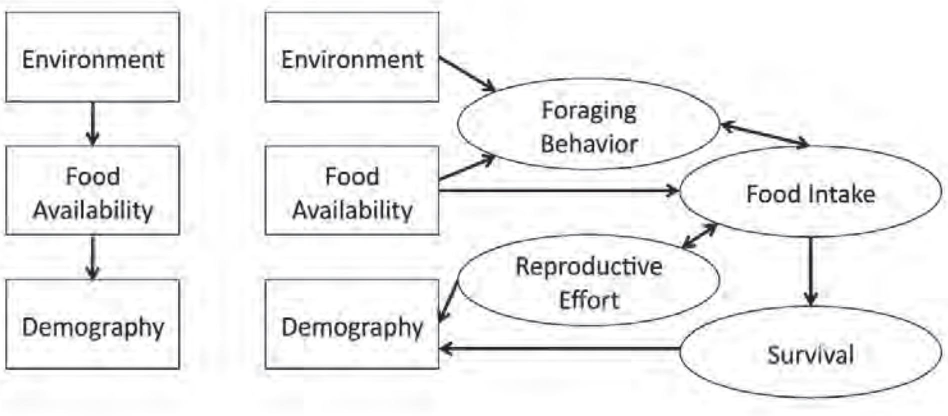
Black-legged kittiwakes nesting on St. Paul Island. Several chicks are visible in nests, for example at lower left and middle left of the photograph..

The Big Picture

Many different populations in the Bering Sea are increasingly likely to experience climate-induced changes in their physical and biological environments. Since adult kittiwakes are central place foragers with high energy requirements, an increased variability of forage patch dynamics, as predicted for polar regions, is likely to influence both the quantity and quality of food available. This would consequently alter the population dynamics of kittiwake colonies, mitigated by stress hormones rising in response to food shortages, with consequent effects on survival and reproduction.

BEHAVIORAL AND LIFE HISTORY MODELING OF SEABIRDS IN THE NORTH PACIFIC
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

Fig. 1



Behavior is the first response to changing environment. Left hand panel: When organisms are assumed to have fixed, stereotyped responses to food availability, the effects of the environment on population demography (growth, survival, and reproduction) are linear (but may still be complicated). Right hand panel: On the other hand, if organisms have flexible responses through foraging and reproductive behavior, the links between climate, food availability, and demography become more intricate and less linear. The objective of our work was to explicate these linkages using state-dependent life history theory.

the colonies on Bogoslof Island and the Pribilof Islands, a remaining puzzle is understanding how the regime shifts in the Northeastern Pacific of the late 1970s, and the associated changes in food, drove colony declines in the Bering Sea, while other colonies in the Aleutian Archipelago increased in size.

How We Did It

Our study combined mathematical models, statistical analysis and experimental manipulation. We examined the statistical relationship between the stress hormone corticosterone and the mortality of birds. We also used statistical methods to test if inter-annual changes in the Pacific Decadal Oscillation, winter ice cover, or local sea-surface temperature predict changes in productivity (fledglings per nest) or stress hormones. Through experimental manipulation of food availability, we studied aspects of reproductive performance associated with food availability. Population modeling helped us determine whether the mortality rates associated with persisting in a breeding attempt despite high levels of stress hormones caused the birds to sacrifice more lifetime reproductive output than they gain from one year's breeding. Modeling also helped relate the effects of environment and energy resources on kittiwake growth, fledging age, survival from hatching to first breeding and productivity.

Why We Did It

Although animals have evolved to deal with environmental stress, there are limits to their ability to do so, and it is important to know if climate change will push animals beyond these limits. If one thinks that responses to environmental variation are fixed and inflexible (left panel of Figure 1), then the limits are hard boundaries, but when behavioral flexibility allows animals to adjust to changing environments (right panel of Figure 1)—which is true, even in 'simple' animals—then the limits are more complicated to understand. Characterizing them cannot be done observationally and is very difficult to do experimentally. That is, we cannot wait until the climate changes and then see how animals respond if we want to have a chance of mitigating effects; even if we could do feeding experiments on caged animals, it would be difficult to interpret them and scale them up. Modeling provides a natural way for projecting the behavioral responses and the boundaries beyond which changing climates will have seriously deleterious effects.

Authors:
Marc Mangel, University of California, Santa Cruz
William H. Satterthwaite, University of California, Santa Cruz
Simone Vincenzi, University of California, Santa Cruz

Co-authors:
Scott A. Hatch, US Geological Survey, Alaska Science Center
Alexander S. Kitaysky, University of Alaska Fairbanks
John F. Piatt, US Geological Survey, Alaska Science Center

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

The Impact of Changes in Sea Ice Extent in the Eastern Bering Sea

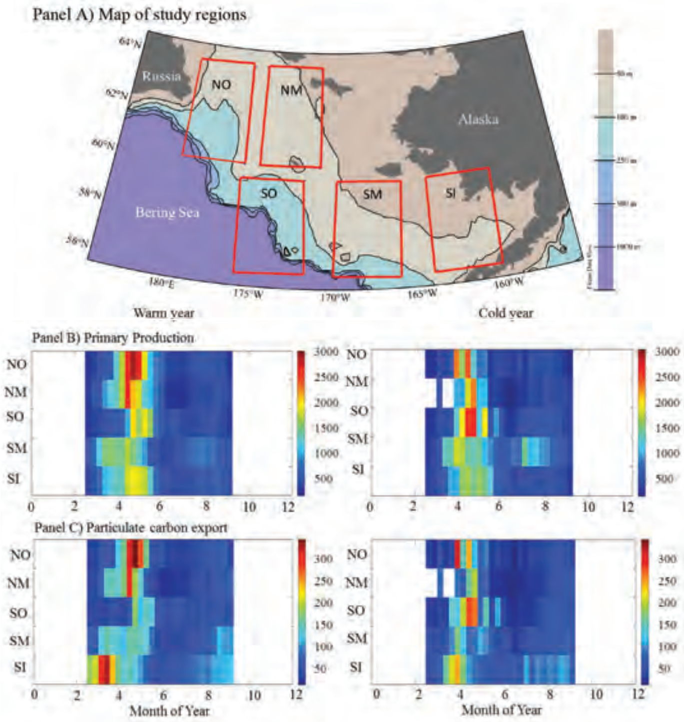
MODELING A LARGE-SCALE ECOSYSTEM RESPONSE TO GLOBAL OCEAN WARMING

Phytoplankton form the base of the food chain in the sunlit ocean and support higher trophic levels, such as fisheries. Previous studies have linked changes in phytoplankton community to indices of natural climate variability (e.g., El Niño), but little is known about ecosystem responses to ocean warming. We used a combination of new field measurements and an ecosystem model to estimate changes in phytoplankton production and removal under actual cold and simulated warm years over the southeastern Bering Sea shelf.

Using ecosystem model simulations, we observed that phytoplankton production over the Bering Sea shelf in warm years was only slightly higher than during cold years. Associated with this increased phytoplankton productivity was a simulated increase in export of phytoplankton material to the ocean floor (Figure 1). Simulated phytoplankton carbon export in both warm and cold years showed strong seasonal patterns; a result validated by direct observation in the cold years of the Bering Sea Project. Phytoplankton carbon export was low in the marginal ice zone (MIZ),

continued on page 2

Fig. 1



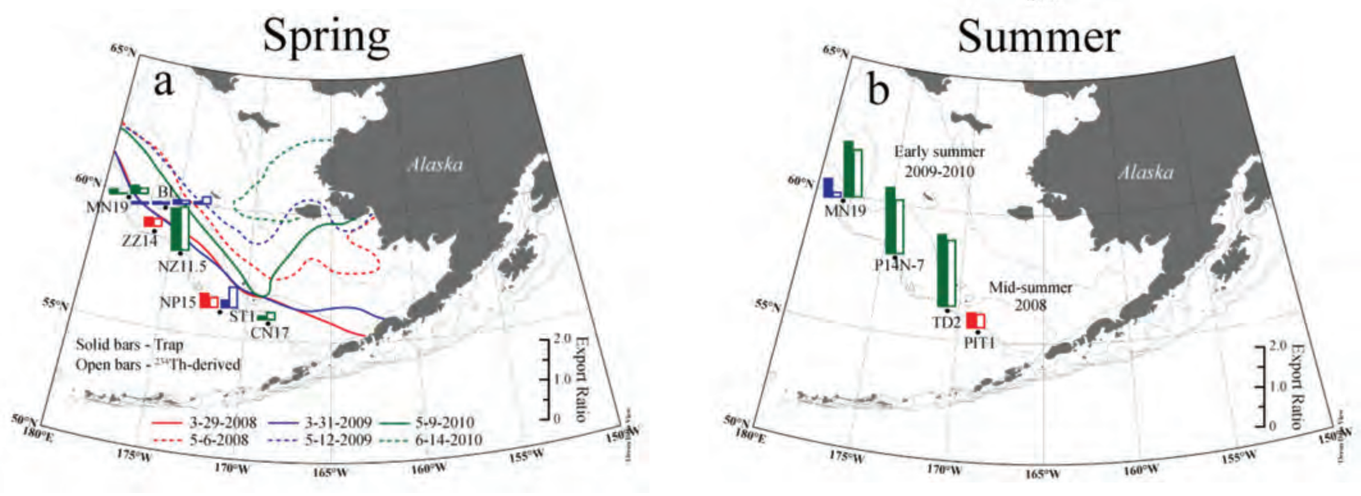
Focus regions for our modeling simulations (panel A). Rates (mg C m-2 d-1) of phytoplankton primary production (panel B) and particulate carbon export flux (panel C) for warm (left plots) and cold (right plots) years in each study region and for each 8-day average time window.

The Big Picture

The Bering Sea supports one of the world's most productive ecosystems and sustains a large fraction of the total U.S. fisheries harvest. The Bering Sea is potentially susceptible to future climate change, but it is not known how, or to what extent, a warmer Bering Sea might alter the fate of phytoplankton production within the ecosystem and hence affect the yield of this important fishery. A key hypothesis of our Bering Sea Project is that climate change shifts the fate of organic matter from the pelagic to the benthic environment; and, further, that such external forcing on the ecosystem is highly dynamic, non-linear, and unpredictable.

A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

Fig. 2



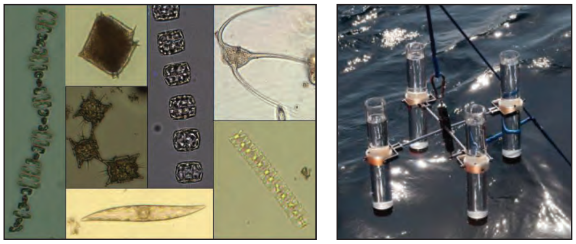
Spring (a) and summer (b) export ratios determined during 2008-2010. Solid and dashed lines represent ice-edge maximum and minimum during spring sampling periods. Solid bars indicate trap-derived and open bars represent Thorium-derived export ratios. Colors: red (2008), blue (2009), and green (2010).

unless the area was experiencing an active phytoplankton bloom, and increased through late spring and early summer. This phytoplankton carbon export to the benthos represented a significant fraction of primary production, i.e., the export ratio (Figure 2).

How We Did It

We conducted spatially extensive measurements of phytoplankton production, community structure, and associated particulate carbon export during spring and summer from 2008-2010. We supplemented this observational dataset with phytoplankton production model simulations derived from spatial distributions of remotely sensed phytoplankton biomass and knowledge of their physiology. Using sequential ocean color images and a mathematical model constraining the relationships between elements in the ecosystem model, we estimated the partitioning of organic carbon between higher trophic levels and the ocean floor (Figure 1). These ecosystem model simulations were validated for cold years by comparison to directly measured particulate carbon export derived from sediment traps (Figure 3). Other carbon fluxes are currently being compared to distributions of data collected by the Bering Sea Project to better understand the partitioning of carbon within the Bering Sea ecosystem so that the potential implications for the fishery may be assessed.

Fig. 3



Images of Eastern Bering Sea plankton, common diatoms and dinoflagellates, (left panel) and the sediment trap used to capture them as they sink from the surface ocean (right panel).

Why We Did It

The combination of field measurements and model analysis has led to an improved understanding of the regional and temporal (warm vs. cold periods) variability in the magnitude of phytoplankton production and its fate within the Bering Sea ecosystem. From this study, we are developing a more mechanistic understanding of how carbon and energy flow through the plankton community to commercially important species in a changing Bering Sea.

S. Bradley Moran, Graduate School of Oceanography, University of Rhode Island (URI)

Michael W. Lomas, Bigelow Laboratory for Ocean Sciences

Matthew S. Baumann, Graduate School of Oceanography, URI

Roger P. Kelly, Graduate School of Oceanography, URI

Chunli L. Liu, Marine College, Shandong University, China

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Return of the Zooplankton

RECENT COLD CONDITIONS A BOON FOR CRUSTACEAN ZOOPLANKTON

Copepods (e.g., *Neocalanus cristatus*) and krill (e.g., *Thysanoessa inermis*) are miniature shrimp-like animals that are critical to the diets of commercially valuable fish, marine birds and cetaceans. They are an essential link between the base of the marine food web and larger animals. But the population of these large crustacean zooplankton (LCZ) in the Bering Sea varies depending on ocean conditions. The population of LCZ crashed during a string of years with warmer water (2000-2005), and has recovered in recent years as water temperatures cooled (Figure 1).

What caused such a large swing in LCZ population? Was there insufficient food during the warm years (less phytoplankton and tiny micro-zooplankton), or was there more grazing from fish and mammals keeping LCZ populations low? And how are such changes in the food web linked to changes in climate and ocean circulation?

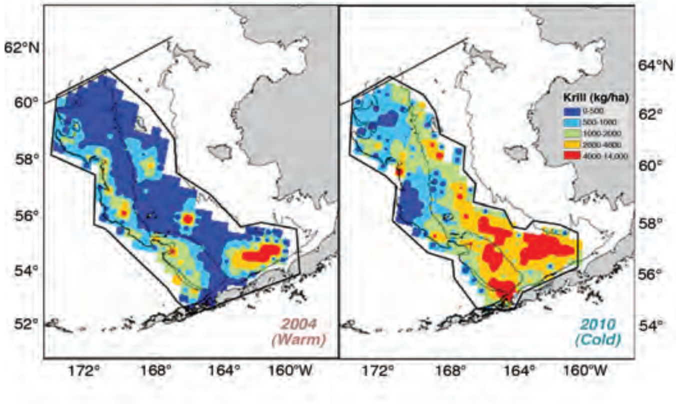
How We Did It

Our approach was to analyze bottom-up (food supply) and top-down (predation by fish) controls of LCZ standing stocks, including climate, physics, primary production, micro-zooplankton production, and predation, and to examine how LCZ production was partitioned among top predators under varying climate scenarios. Because the eastern shelf has different physical domains (regions with different ocean properties) these questions were examined in defined regions of the shelf to elucidate how differences in water column structure and mixing processes affect the flow of carbon and energy.

Using data from the past decade, we examined spatial and temporal distributions of predator and prey fields, and the influence of climate and currents on those distributions. Hypotheses and questions were

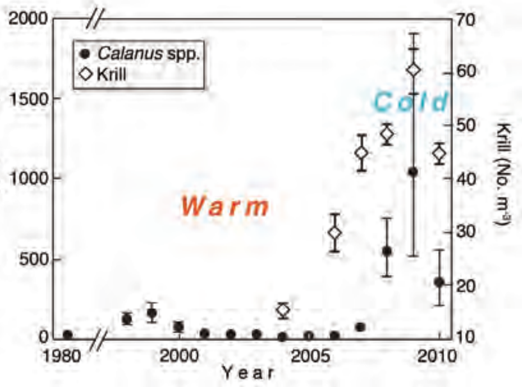
continued on page 2

Fig. 2



In cold years, krill were more abundant and more widely distributed across the shelf compared to warm years as determined by acoustic surveys of krill biomass.

Fig. 1



Associated with a change from warm conditions (2000-2005) to cold conditions (2007-2010) was an increase in the number of Calanus copepods and krill on the eastern Bering Sea shelf. Vertical bars represent the standard deviation of the data.

The Big Picture

The Bering Sea shelf supports one of the world's most productive fisheries and accounts for a large fraction of U.S. fisheries landings. This system is highly susceptible to climate change, but our understanding of that susceptibility remains poor. In this study, we addressed several key Bering Sea Project hypotheses, including the influence of climate and ocean processes on food availability for fish and mammals (bottom-up processes), and dynamic ecosystem controls from predation (top-down processes). We examined how the presence or absence of sea ice over the eastern shelf in spring influenced the flow of energy through the pelagic ecosystem in the eastern Bering Sea, particularly the distribution, standing stock, and trophic role of large crustacean zooplankton (LCZ).

IMPACT OF SEA-ICE ON BOTTOM-UP AND TOP-DOWN CONTROLS OF CRUSTACEAN ZOOPLANKTON AND THE MEDIATION OF CARBON AND ENERGY FLOW IN THE EASTERN BERING SEA
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

also addressed through integrated models and by expert panels at two interdisciplinary workshops.

We found that the spatial distribution of krill differed between warm and cold years with greater abundance over the shelf during cold periods (Figure 2). This may be the result of changes in ocean circulation as there was more southward flow during cold years that brought ice and colder water over the southern shelf, which in turn excluded some predators from the shelf. However, when using a multivariate regression analysis of predator-prey biomass, it did not appear that Walleye Pollock (*Gadus chalcogrammus*), the major fish predator, exerted top-down control on krill populations (Figure 3).

In spring, phytoplankton and ice algae were the main food source for LCZ, but in summer, phytoplankton were smaller and micro-zooplankton were the major food source for LCZ. Energy flow through the ecosystem appeared to be different in warm and cold conditions (Figure 4). In warm years, the phytoplankton bloom occurred later, and sea ice and ice algal communities were less extensive. In cold years, algae growing on the bottom of the ice, and earlier ice edge blooms, gave the LCZ an early boost of food, helping sustain egg production and survival of juveniles. This may partially explain the return of LCZ during recent cold years.

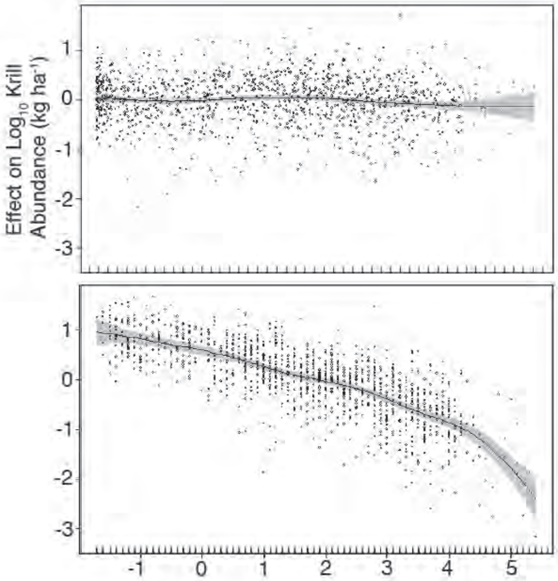
Why We Did It

Results garnered from these studies will provide a better understanding of regional and temporal (seasonal, interannual) variability in secondary production in the eastern Bering Sea and its ability to support major fisheries. From this study, we hope to develop new mechanistic and conceptual models of carbon and energy flow, and to provide improved predictions of the magnitude and fate of secondary production in an ever-changing Bering Sea.

Calvin Mordy, University of Washington (UW)
Seth Danielson, University of Alaska Fairbanks
Lisa Eisner, National Oceanic and Atmospheric Administration (NOAA)
George Hunt, UW
Michael Lomas, Bigelow Laboratory for Ocean Sciences
Jeff Napp, NOAA
Patrick Ressler, NOAA
Mike Sigler, NOAA
Phyllis Stabeno, NOAA

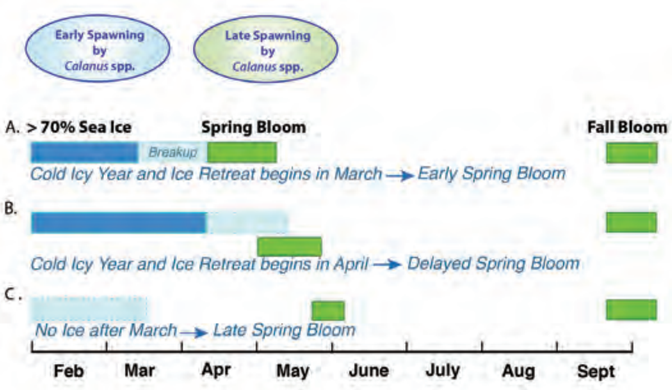
The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 3



Partial effects of pollock biomass and bottom temperature in a multivariate model (GAM) of krill biomass density. Taken together, the flat pollock curve and steep temperature curve suggest that krill abundance is greater at colder temperatures, but is not tightly linked to changes in pollock biomass, casting doubt on top-down control by predation.

Fig. 4



Three scenarios of ice retreat and its influence on the timing of the spring phytoplankton bloom in the southeastern Bering Sea. If sea ice (blue) is present after mid-March (Scenarios A and B), a phytoplankton bloom (green) is present during sea ice retreat. If ice retreat is early (Scenario C), a spring bloom usually occurs in May.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Hungry Fish Make a Difference

LINKING CLIMATE AND KRILL ABUNDANCE

Many fish, seabirds, and whales feed on krill, but there is only so much to go around. Every year, krill (or euphausiids) abundance peaks in late spring – early summer, and bottoms out at the end of winter. Migrations and movement are tuned to the seasons, but what happens when there is overall less or more krill, as can happen in cold and warm years? Do fish make a noticeable dent on the available krill? How much and where?

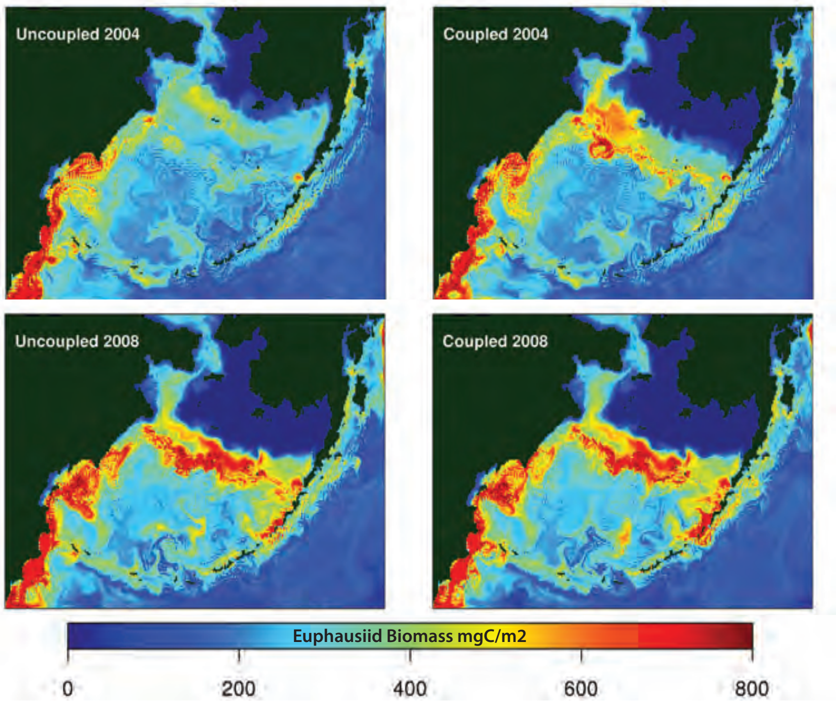
Krill abundance is higher during cold years and lower during warm years. The amount of energy fish need to grow also changes with temperature. To grow the same amount, fish require less energy in cold temperatures, more in warm temperatures, thus eating less krill in cold years and more in warm years. This creates large areas where krill is grazed down in warm years but not in cold years, impacting krill predators such as forage fish, seabirds, and marine mammals (Figure 1).

continued on page 2


REEM/AFSC/NOAA

Hungry fish – warm temperatures increase fish metabolism, meaning they eat more krill in warm years, changing the availability of krill to other predators throughout the Bering Sea shelf and slope.

Fig. 1



Average krill biomass in the eastern Bering Sea shelf and slope for 2004 (warm year) and 2008 (cold year) assuming zooplankton mortality is proportional to biomass (uncoupled) and linking a bioenergetics fish model (coupled).

The Big Picture

Forage fish are the link between zooplankton and many larger fish-eating predators such as large fish, seabirds and marine mammals. For example, walleye pollock is the single most abundant fish on the eastern Bering Sea shelf, with an estimated 6.5 million tons per year consumed by predators. It also supports a fishery of over 1,000,000 tons annually, with revenues upwards of 2 billion dollars. Keeping track of krill and forage fish response to different climate conditions, and the cascading effects on the food web, builds on our understanding of processes such as population growth, feeding grounds, "hot spots," consequences of fat and skinny krill, as well as fishermen's behavior. Combined with climate forecasts, it has the potential to complement current conservation and management in the Bering Sea with more proactive and strategic actions.

FORAGE AND EUPHAUSIID ABUNDANCE IN SPACE AND TIME (FEAST)
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

How We Did It

We used a 3D model for oceanography, nutrients and plankton (NPZ) constructed for previous work, and we added data for several species of fish at different lengths based on historical databases from the National Marine Fisheries Service and National Oceanic and Atmospheric Administration. Rather than assuming zooplankton gets eaten in proportion to their biomass, we assumed it gets eaten according to fish energy needs or bioenergetics. We gave the different types of zooplankton (such as krill) and fish values in calories, and then based the fish consumption and growth on how many calories they ate and how they spent them on swimming, living and growing, all of which is affected by temperature. We then ran the model for the entire Bering Sea, estimating everything from oceanography to plankton dynamics, fish numbers, distribution, length, and weight. This requires a lot of calculations, so we use a supercomputer, which means we divide the whole region into small squares and send them out to 384 processors that talk to each other. One simulated year takes about 16 hours to run.

Why We Did It

In the eastern Bering Sea most of what we know about fish occurs in summer and early fall, and relates to their feeding habits, species abundance and their distribution. We know very little about the rest of the year, including interactions with climate, winds, currents or zooplankton. We are now working on integrating oceanography with zooplankton and fish dynamics. Because many predators eat either zooplankton or forage fish, it is important to understand how much and where zooplankton (like krill) is consumed by forage fish (small fish like young pollock, capelin and herring) year round and in multiple years. We wanted to quantify the difference between assuming that fish predation is proportional to krill biomass (uncoupled mode) versus using bioenergetics (coupled mode) (Figure 2), and to measure changes in the spatio-temporal availability of krill (Figure 3).

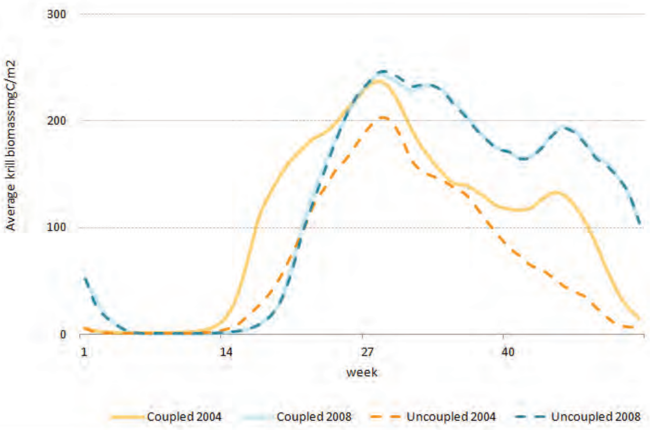
Ivonne Ortiz, University of Washington (UW)/ Alaska Fisheries Science Center (AFSC), National Oceanic and Atmospheric Administration (NOAA)

Kerim Aydin, AFSC, NOAA

Al Hermann, UW / Pacific Marine Environmental Laboratory, NOAA

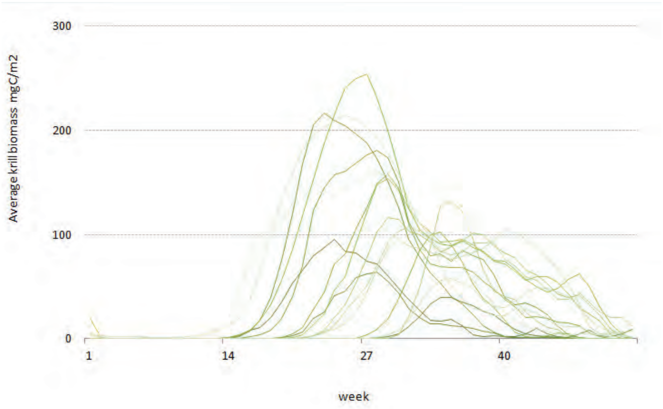
The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



Average krill biomass in the eastern Bering Sea shelf and slope for 2004 (warm year) and 2008 (cold year) assuming zooplankton mortality is proportional to biomass (uncoupled) and linking a bioenergetics fish model (coupled).

Fig. 3



Variability in space and time of krill biomass in different regions of the eastern Bering Sea shelf and slope as estimated for 2004 using the fish bioenergetics model to estimate predation on krill.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Observation Synthesis and High Resolution Numerical Modeling

WHY IT'S NECESSARY IN THE BERING SEA

Over the past several years, the Bering Sea Project has accumulated an unprecedented amount of ocean and sea ice observations. These have been obtained in different seasons using different platforms (e.g CTD, moorings, Argo floats, surface drifters, moorings). The rich collection of Bering Sea Project *in situ* and satellite observations now provide an excellent opportunity for synthesis, through modeling and data assimilation (DA), in order to improve our understanding of the impacts of changes in the physical forcings of the Bering ecosystem in response to climate change. Synthesis of available data allows us to improve estimates of the state of the Bering Sea and to obtain dynamically balanced fields of all physical parameters. After assimilation, we will be able to quantify the volume, heat, and salt transports over the eastern Bering Sea. High-resolution computer modeling will complement the DA efforts, providing a tool for studies of processes that influence transports, mixing, and hydrographic changes in the Bering Sea on temporal scales from hours (tidal) to years (inter-seasonal).

How We Did It

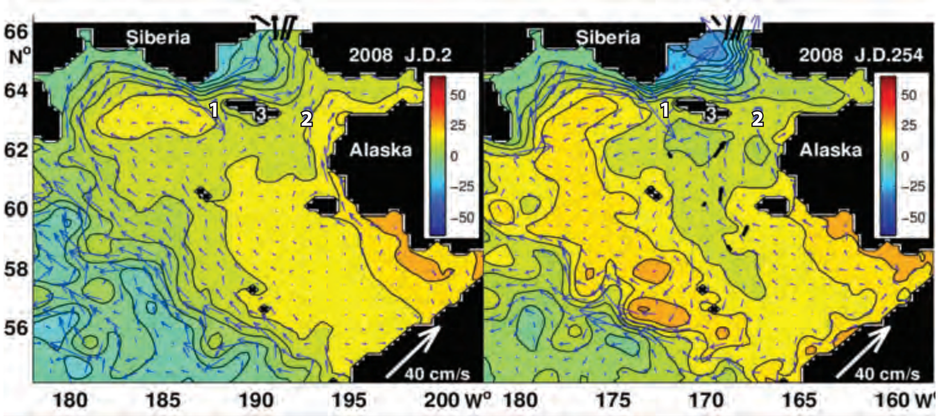
Two approaches were used in our research. The first combines a technique called Four-Dimensional Variational Data Assimilation (4DVAR), an existing numerical ocean model, and an optimal interpolation algorithm used in the Bering Ecosystem STudy ice–ocean Modeling and Assimilation System (BESTMAS). The technique is based on the least squares fit of the model solution to observations. It demands thousands of model runs and significant computational resources. However, as an advantage, 4DVAR allows assimilation

continued on page 2

The Big Picture

There has been a significant increase in operational *in situ* and satellite observations during the last decade. This creates the potential for more accurate hindcasting and forecasting of circulation, water, and ice properties in the region. These capabilities are boosted by new and more sophisticated and efficient data assimilation systems, based on high-resolution models that include biogeochemical components. The resulting patterns enhance our ability to understand and manage the rich eastern Bering Sea ecosystem.

Fig. 1



Snapshots of reconstructed sea surface height (cm; see color bar) and surface circulations in the Bering Sea in 2008 (left: 2 January; right: 10 September). Thicker black arrows designate the locations of the moorings in the Bering Strait and the Eastern Bering Sea shelf. Numbers 1,2,3 designate the Anadyr and Spanberg straits and St. Lawrence Island, respectively.

of any type of observations. In our case, the variety of assimilated data includes both *in situ* (e.g., temperature, salinity, velocity) and satellite (Sea Surface Height (SSH), Sea Surface Temperature (SST), ice concentration, velocity) observations. Our results indicate intensification of the Bering Slope flow in winter and enhanced variability of circulation over the Eastern Shelf during the summer and fall (Figure 1).

The second approach uses high-resolution numerical modeling. The dominant spatial scale of variability in the Bering Sea (the scale of the width of coastal jets and eddies) may be as small as 20 km. Because of the large area of the Bering Sea and the computational cost of resolving ocean features on these scales, most previous modeling studies have failed to achieve sufficient resolution to represent many important phenomena. We developed a 2-km horizontal resolution model that describes ocean circulation in the Eastern Bering Sea. This model is run for the ice-free period of July-October 2009. It exhibits correct ocean behavior, as verified using the Bering Sea Project mooring data along with Argo drifters and satellite SST and SSH. This model allowed us to analyze variability in flows through numerous passes of the Aleutian Island chain and provided a dynamic picture of the erosion of the "cold pool" (an area in the middle of the Bering Sea shelf where the dome of very cold near-bottom water is capped by the surface layer of warmer water in summer; Figure 2).

Why We Did It

Quantifying the currents in the Bering Sea is important for depicting accurate patterns of physical and biochemical parameters in the region. For example, strong flow through the Spanberg Strait during the late summer and fall (Figure 1) may significantly affect conditions in the cold pool that are extremely important for local biological production. Other, smaller-scale motions, evident in our reconstructions, may play a critical role in eroding the cold pool and providing nutrients from near the sea floor to the surface mixed layer of the Bering Sea shelf.

The cold pool frontal boundary (Figure 2) erodes during summer at varying rates at different locations, leading to a highly corrugated frontal boundary. The Pribilof Islands act as a region of enhanced cold pool erosion due to tidal mixing. The highly variable rate of erosion of the pool and the characteristics of its boundary introduce ecological patchiness, and potentially alter the rate at which larvae and juvenile fish can be transported or migrate from recruitment regions near the shelf break to settlement zones on the inner shelf.

Gleb Panteleev, International Arctic Research Center (IARC), University of Alaska Fairbanks (UAF)

Jacob Stroh, IARC, UAF

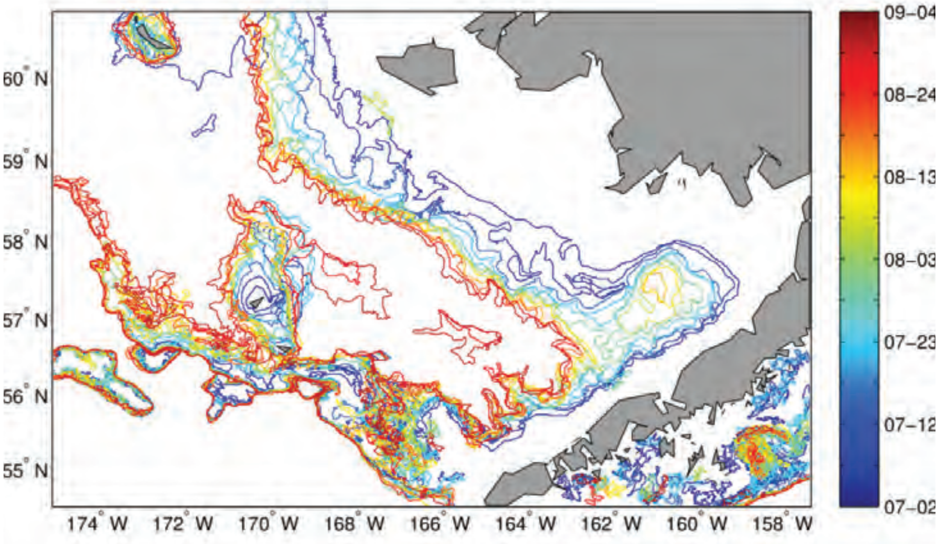
Alex Kurapov, College of Oceanic and Atmospheric Sciences (COAS), Oregon State University (OSU)

Scott Durski, COAS, OU

Jinlun Zhang, Applied Physics Laboratory (APL), University of Washington (UW)

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Project and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



This figure illustrates the seasonal retreat of the cold pool, from early July 2009 through early September 2009, in the model simulation. Contour lines indicate the position of the cold pool front, as indicated by locations where the 3.5 °C isotherm intersects the sea floor in the high-resolution Bering Sea model. Color indicates the date for which the contour line corresponds. Rapid erosion of the cold pool is observed especially early in the season and around the Pribilof Islands. Erosion along the edges of the cold pool is highly irregular and likely due to a combination of tidal and convective mixing effects.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Distributions of Bering Sea Forage Fish

THE MOVING MIDDLE OF THE FOOD WEB

Forage fish, which include capelin, herring, and the young life stages of walleye pollock and Pacific cod, are food for many fish, birds, and mammals in the Bering Sea. These predators are ecologically important, commercially valuable, and the focus of traditional harvest. Evidence suggests that forage fish distributions (vertically within the water column and horizontally across the Bering Sea) can change from year to year, and yet we don't fully understand why. Knowing that climate change may impact the available habitat for forage fish, it is necessary to understand the *where, how many,* and *why* of fish distribution to predict how changes may affect forage fish populations and the predators that count on them as prey.

How We Did It

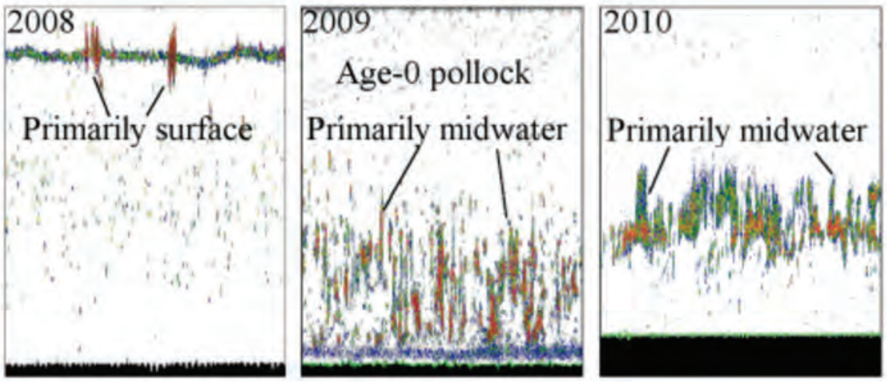
At sea, we used echosounders and trawling to map distributions of forage fish between BASIS (Bering Aleutian Salmon International Survey) survey stations in 2008-2010. The analysis was expanded to include existing acoustic data from 2006-2007. In 2008, age-0 pollock were primarily found in the surface water, less than 35 m deep (Figure 1). In both 2009 and 2010, highest densities were found in dense schools in the midwater, more than 35 m deep (Figure 2). Both age-0 Pacific cod and capelin had high densities in the surface in 2010 as compared to 2009 (Figures 3 and 4), but no or low densities in the midwater. We evaluated the influence of physical, biological, and/or climate factors on forage fish distributions. Models varied by species but, in general, temperature, bottom depth, and/or zooplankton prey were important predictors of forage fish presence and density. Interestingly, annual variables, such as storminess in June and sea ice, were sometimes as or more predictive than local conditions at a station.

Why We Did It

Environmental conditions (e.g., temperature, salinity), the availability of zooplankton prey, and

continued on page 2

Fig. 1



Acoustic echograms showing differences in vertical distribution of age-0 pollock in 2008, 2009, and 2010. Bottom depth shown is ~80 m in 2008, ~110 m in 2009, and ~150 m in 2010.

The Big Picture

Forage fish are the critical middle of aquatic food webs throughout the world. Changes in forage fish densities or distributions can affect forage fish recruitment, nesting/breeding success of birds, and/or movements of fish or marine mammal predators that are important for commercial or traditional harvest. Understanding how forage fish distribute themselves is critical when evaluating potential impacts of climate change, and to fulfill the requirements of ecosystem-based approaches to fisheries management. Our baseline information can inform Bering Sea models that predict biological responses to climate change and improve methodologies for future abundance estimate surveys.

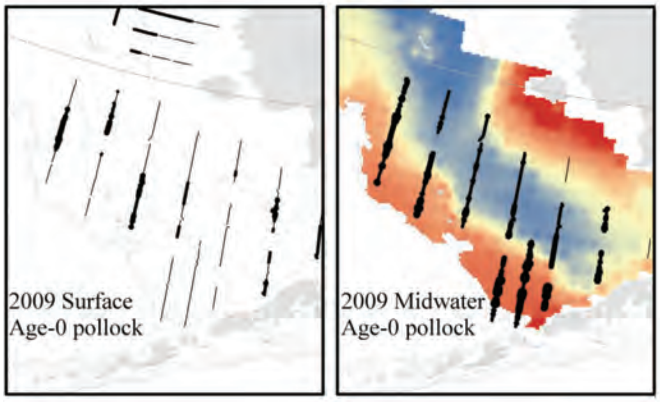
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

vulnerability to predators can all influence survival of forage fish. Distributions may result from a combination of selection of preferred conditions and the influence of water movement in the Bering Sea. If forage fish vertical or horizontal distributions change with environmental conditions, then food availability for predators and our ability to obtain information on forage fish distributions from existing surveys will also change. A comprehensive analysis that included physical, biological, and climate factors was needed to understand what affects forage fish distributions.

Sandra Parker-Stetter, University of Washington (UW)
John Horne, UW
Ed Farley, National Oceanic and Atmospheric Administration, Alaska Fisheries Science Center

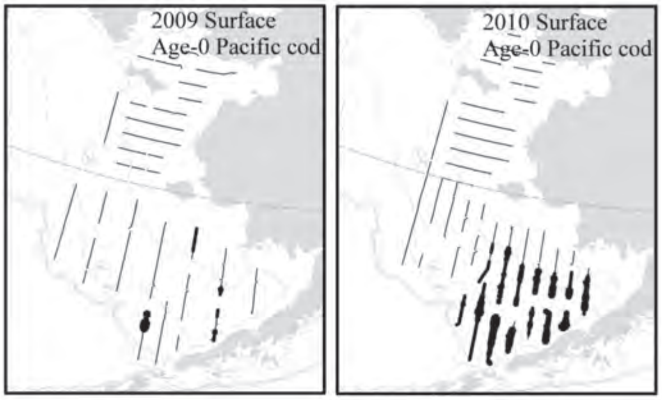
The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



Distribution of age-0 pollock in the surface (left) and midwater (right) in 2009. Larger dots show higher densities. Bottom temperature (ºC) was an important predictor of midwater pollock density and is shown on the midwater figure (red is warmest). Although there were few age-0 pollock in the surface zone in 2009, there were regions of high densities in the midwater zone. Bottom temperature data courtesy of Bob Lauth (NOAA-AFSC).

Fig. 3

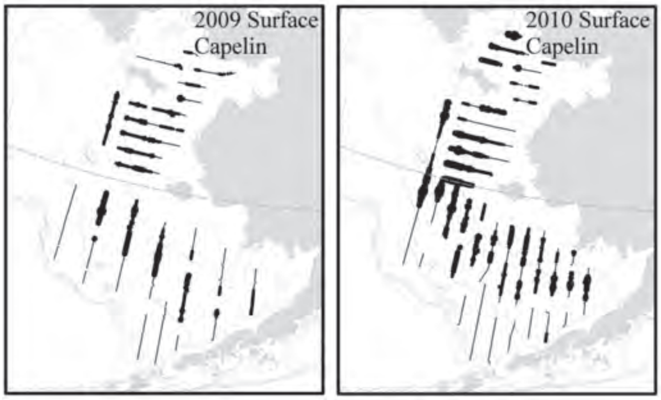


Distribution of age-0 Pacific cod in the surface waters in 2009 (left) and 2010 (right). Larger dots show higher densities. High densities of age-0 Pacific cod were observed in 2010 in regions that had low densities in 2009.


Sandra Parker-Stetter

Forage fish, flatfish, and jellyfish from a surface trawl catch on the R/V Oscar Dyson *in 2010.*

Fig. 4



Distribution of capelin in the surface waters in 2009 (left) and 2010 (right). Larger dots show higher densities. Capelin were found in the same regions in both years, but densities were higher and more continuous along transects in 2010.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

The Early Life of Walleye Pollock on the Eastern Bering Sea Shelf

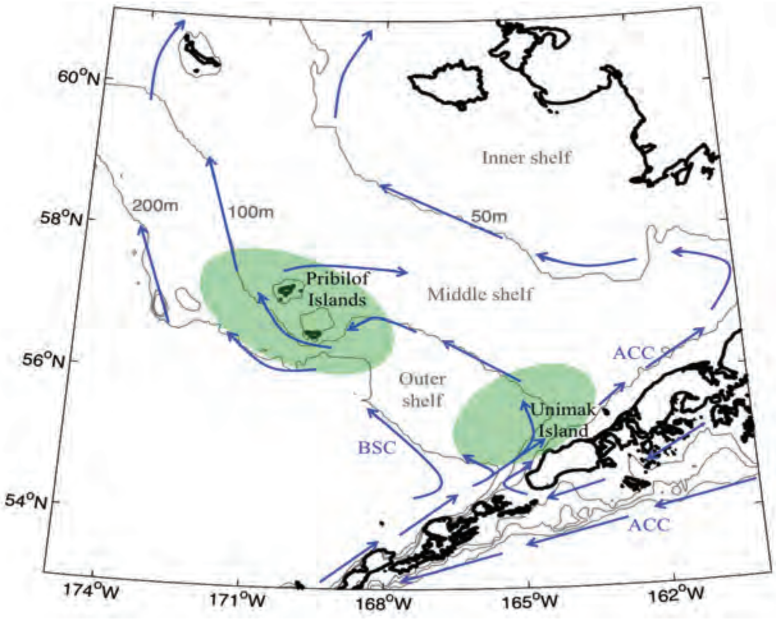
DISTRIBUTION SHIFTS IN WARM AND COLD YEARS

Fish eggs and larvae are very vulnerable within the first few months after being spawned. They are only a few millimeters long, and rely on ocean currents to take them from the spawning grounds to their nursery areas. Due to starvation and predation, less than one percent survive. To maximize their chances, adult fishes have evolved to spawn their eggs at the times and places that will lead to successful transport and higher survival rates of their larvae.

In the eastern Bering Sea (Figure 1), sea ice may affect when and where adult Walleye Pollock (*Gadus chalcogrammus*) spawn their eggs, and current patterns affect where the eggs and larvae drift. This area recently experienced an exceptionally warm period (2001-2005) followed by a prolonged cold period (2007-2012). During cold years, winter sea ice extended farther south and offshore, creating a large, cold pool of bottom water that adult pollock avoid. In the warm years this cold pool was much smaller and there appeared to be stronger flow to the east and onto the shelf. Research cruises observed that pollock eggs and larvae were found further onshelf in warm years than in cold years. We wanted to know how

continued on page 2

Fig. 1



The dominant currents (blue lines) and Walleye Pollock spawning areas (green ovals) of the Eastern Bering Sea. The Alaska coastline is shown in black and the 50, 100, and 200 m isobaths in gray. ACC – Alaska Coastal Current; BSC – Bering Slope Current.

The Big Picture

Spawning time, spawning location, and transport by currents affect the location and survival of fish eggs and larvae. The eastern Bering Sea recently experienced several warmer-than-average years followed by colder-than-average years. Observations of the spatial distribution of Walleye Pollock eggs and larvae indicated that larval distributions were shifted from the outer continental shelf towards the middle shelf in warm years. We used a computer model to simulate how pollock eggs and larvae are transported by currents, grow over time, and move up and down in the water column. Simulations suggest that differences in adult spawning location between warm and cold years play a bigger role than differences in water transport alone or differences in the time of spawning.

THE VARIABLE TRANSPORT OF POLLOCK EGGS AND LARVAE OVER THE BERING SHELF: A MARRIAGE OF PHYSICS AND BIOLOGY
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

differences between cold and warm years resulted in this pattern.

How We Did It

We developed a model that simulated the transport, biology, and behavior of individual pollock eggs and larvae. Simulated spawning areas were based on where adult pollock in spawning condition have been found. Tens of thousands of eggs were "released" in the model at seven spawning times. We compared where different size classes of eggs and larvae were located in warm (1996, 2002, 2003, 2005) and cold (1997, 1999, 2000, 2006, 2008-2012) years by calculating the center of the distribution of each size class. We considered four different scenarios. In each, the ocean currents were specific to the simulated year and were based on observed climate conditions, while spawning areas and times differed among scenarios: (a) Spawning time and location were the same for warm and cold years. (b) Spawning locations were the same, but spawning time was 40 days later in cold years, simulating the possibility that adult fish waited for sea ice retreat before spawning. (c) Spawning time was the same, but the spawning areas were increased in size in warm years, simulating the expansion of spawning adults into areas without sea ice. (d) Spawning time was the same, but the spawning areas were reduced in size in cold years, simulating avoidance of sea ice-covered areas by adult fish.

When spawning time and location were held constant (Figure 2a), and when spawning time was 40 days later in cold years (Figure 2b), the centers of distribution of pollock eggs and larvae did not differ much between warm and cold years, suggesting that climate-related differences in ocean circulation and delays in spawning time are not sufficient to cause observed changes in distributions. The distribution of simulated eggs and larvae resembled observations when spawning areas were expanded in warm years (Figure 2c). The simulation that produced distributions most comparable to the observations was when spawning areas were decreased offshore in cold years (Figure 2d), but the differences between warm and cold years were not as large as those observed. We conclude that the dissimilar distributions of eggs and larvae in warm and cold years most likely resulted from spawning area shifts in response to changes in the presence and extent of sea ice.

Why We Did It

Related studies have shown differences in prey availability between warm and cold years, and fewer pollock surviving to adulthood in recent warm years with less sea ice. We are currently investigating the cause of these observations. We need a better understanding of these connections because climate change and the associated warming of the arctic and subarctic not only affects the pollock population and therefore the entire ecosystem of the eastern Bering Sea, but also the people who depend on pollock for their livelihood.

Colleen M. Petrik, University of Alaska Fairbanks (UAF)

Janet T. Duffy-Anderson, National Oceanic and Atmospheric Administration (NOAA) Alaska Fisheries Science Center

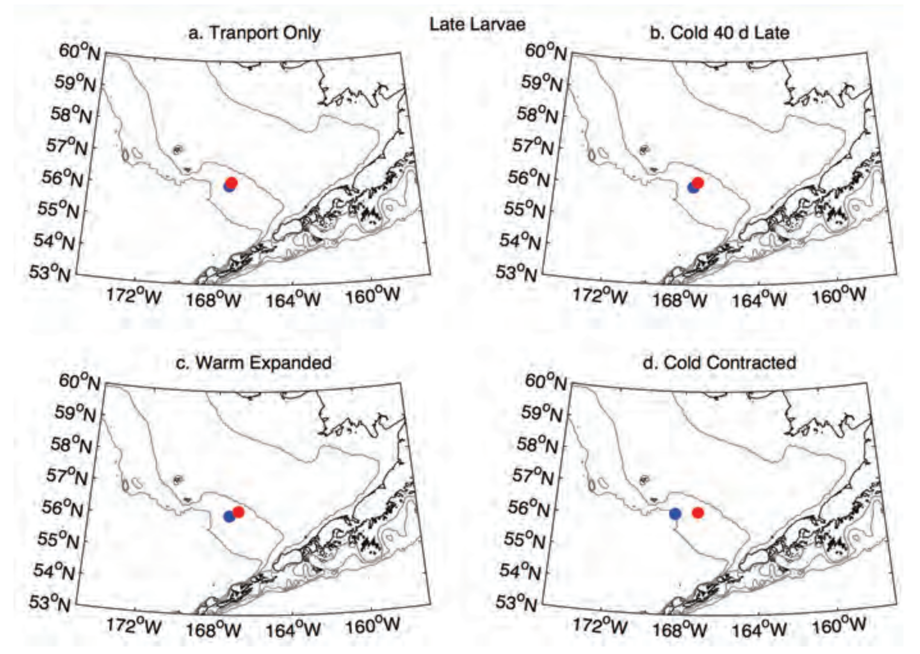
Franz Mueter, UAF

Katherine Hedstrom, UAF

Enrique Curchitser, Dept. of Environmental Sciences and Institute of Marine and Coastal Sciences, Rutgers University

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



Modeled centers of gravity of late stage (10-40 mm Standard Length) larvae in cold (blue) and warm (red) years for all 4 scenarios: (a) spawning time and location were the same for warm and cold years (the red dot is on top of the blue dot); (b) spawning locations were the same, but spawning time was 40 days later in cold years; (c) spawning time was the same, but the spawning areas were expanded in warm years; (d) spawning time was the same, but the spawning areas were contracted in size in cold years.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Zooplankton Populations in the Eastern Bering Sea

LINKING CLIMATE, ZOOPLANKTON AND FISHERIES

Zooplankton are large and small animals, mostly invertebrates, that drift in the water. Information on zooplankton abundance is being used by the Bering Sea Project to assess the health of the Bering Sea ecosystem and to aid in understanding the potential effects of global climate change on Bering Sea fisheries. Since the Bering Sea sustains large commercial fisheries and subsistence resources for native communities, understanding the potential effects of climate change on zooplankton and the fish populations that feed on them will help policy makers plan for and mitigate climate-related impacts on the fishing and indigenous communities along the Bering Sea coast.

How We Did It

We collected 675 zooplankton samples from the eastern Bering Sea, covering all shelf domains and extending from the Alaska Peninsula in the south to the St Lawrence Island in the north. Because many zooplankton taxa spend daytime in the deep and ascend to the surface during the night, we fished a MOCNESS (Multiple Opening/Closing Net and Environmental Sensing System) at night (Fig. 2) to ensure representative collections. The samples then were brought to the lab and preserved critters were identified and counted. These samples will be stored at the University of Alaska for at least 20 years and made available upon request to future researchers. The data on zooplankton composition and the surrounding environment, which were simultaneously collected with automated sensors during the net tows, were uploaded into the Bering Sea Project interdisciplinary database (beringsea.eol.ucar.edu) for public availability.

continued on page 2

Fig. 1

Russ Hopcroft, NOAA

Pelagic predatory amphipod Themisto libellula *flourish in cold Arctic and Bering Sea waters.*

The Big Picture

Ecosystem studies over the last decade revealed substantial declines in populations of large zooplankton during the warm period of 2002 – 2006. These declines were accompanied by declines in the survival of juvenile pollock, a major commercial fish on the Bering Sea shelf. Since large zooplankton are an important food for young pollock, the declines in large zooplankton are a potential reason for observed declines in survival of young pollock. In addition, large zooplankton are an important food for salmon, herring, capelin, and other large fish species. In the absence of large zooplankton, other large fish were consuming juvenile pollock, thus lowering pollock survival and stock size. As fish stocks decline, the supply of fish to the fishery also declines, resulting in lower incomes and employment in fishing communities. As assessed by the Bering Sea Project, colder temperatures in 2007 – 2010 were accompanied by a recovery of large zooplankton populations. Increases in abundance of large zooplankton during the recent cold period are further evidence that declines in zooplankton during the warm period were temperature-related.

ASSESMENT OF MESOZOOPLANKTON POPULATION AND BIOMASS IN THE EASTERN BERING SEA
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

Fig. 2

Chris Lindner, WHOI

Nighttime deployment of the Multiple Opening/Closing Net and Environmental Sensing System (MOCNESS) off the stern of USCG Cutter Healy.

In addition to increases in populations of large zooplankton during the cold period of 2007 – 2010, large Arctic zooplankton species, such as pelagic amphipod *Themisto libellula* (Fig. 1), occurred in the samples. These arctic species had not been observed in the southern Bering Sea since the 1970s. Arctic species can be an important food source for seabirds and commercial fish, so their reappearance on the Bering Sea shelf is an indication that climate change can impact the Bering Sea ecosystem by changing the species composition of the constituent populations in addition to changing population size.

Why We Did It

The species composition and abundance of plant and animal populations in ecosystems are continuously changing in response to climate. Since climate warming is predicted to occur rapidly in arctic and subarctic environments, these changes in species composition and abundance are likely to accelerate and increase in amplitude. Nevertheless, ecosystems are extremely complex and can change in unpredictable ways. Therefore, sound resource management in a changing world requires continuous assessment of the plant and animal populations to allow resource managers to modify management policies in a timely manner, minimizing the potential impacts of unexpected changes in fish and wildlife populations on the coastal communities that depend on these resources for subsistence and commercial harvests.

Alexei Pinchuk, School of Fisheries and Ocean Sciences, University of Alaska Fairbanks

Ken Coyle, Institute of Marine Science, University of Alaska Fairbanks

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

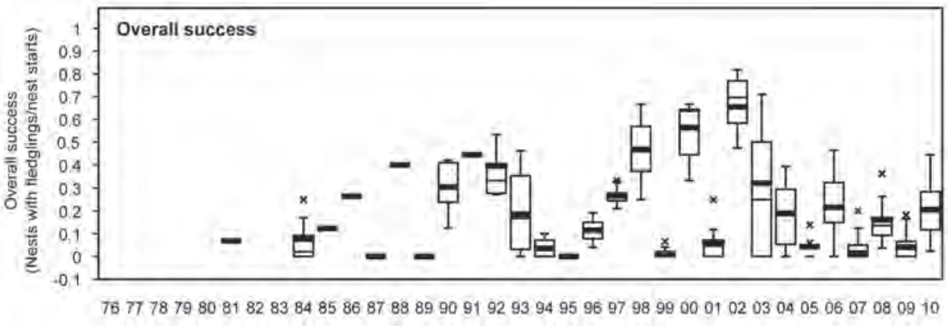
Seabird Diets and Reproductive Success in the Pribilofs

INSIGHTS FROM A 35-YEAR KITTIWAKE DATASET

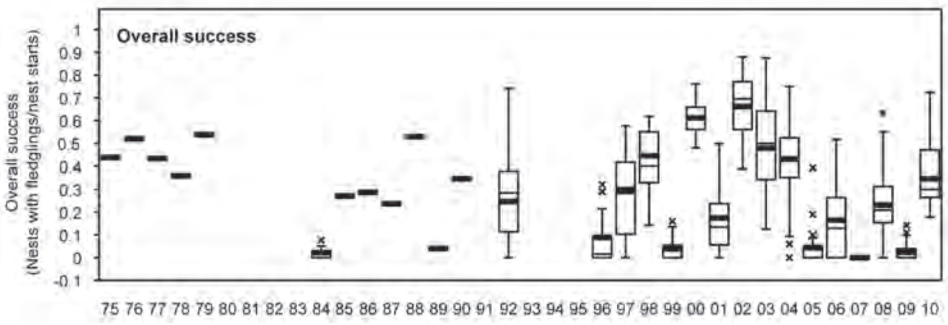
2008-2010 were three cold years on the Bering Sea shelf, characterized by cold ocean temperatures and high ice extent. The reproductive success of black-legged kittiwake (*Rissa tridactyla*) was well below average in 2008-2009 and slightly above average in 2010. A look at our long-term datasets on diet and reproductive success helped us put these years in perspective. Except for a relatively high year at St. Paul in 2009, when there was a patch of age-1 pollock to the northwest of the island, the proportion of pollock in kittiwake diets has decreased since 1975, while that of sand lance has increased. Long-term, kittiwake diet was correlated with some broad-scale climate variables (Arctic Oscillation and regional summer sea surface temperature) but not with local

continued on page 2

Fig. 1



St George black-legged kittiwake reproductive success, 1975-2010.



St Paul black-legged kittiwake reproductive success, 1975-2010.

Brie Drummond

Stephanie Walden holds a kittiwake captured for diet and survival studies. (To prevent disturbing the same bird multiple times, researchers apply a dye that wears off in about a week.)

The Big Picture

The seabird colony-based studies of BSIERP relied heavily on intensive diet, foraging trip, and reproductive success data collected during 2008-2010, the three field seasons of the project. However, understanding relationships among climate variables, seabird diet, and reproductive output requires many more years of study. Otherwise, how would we know what is a good year or a normal year? The seabird cliffs in the Pribilofs are part of the Alaska Maritime National Wildlife Refuge, which has an ongoing annual seabird monitoring program at eight sites around the Alaskan coast. This long-term dataset helps us place in context the detailed diet, foraging behavior, body condition, reproductive success and survival data collected as part of the Bering Sea Project.

SEABIRD COLONY-BASED STUDIES
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

physical variables. When we separated reproductive success into its sequential components, we found that success in earlier parts of the nesting cycle and the previous year were more important predictors of overall productivity than any climate variables. Timing was also an important predictor of laying success for kittiwakes. These relationships suggest a cascade effect, in which adult condition carrying over from the previous year plays a large role in reproductive success. An increase of prey from deeper waters beyond the shelf break (mediated by travel distance required to access prey) and small invertebrates in diets negatively affected fledging success, which may indicate low availability of high quality prey near the colonies.

How We Did It

Most summers since 1975, field crews have spent three months shivering on the fog-shrouded seabird cliffs of both Pribilof Islands, monitoring individually-numbered nests to determine success or failure. For diet studies, adults are captured bringing food back to the nest sites after the chicks have hatched.

Why We Did It

As upper level predators in the marine ecosystem, seabirds reflect fluctuations in the marine environment that influence their prey supply. Studies of seabird diets and reproductive success thus provide insight into the physical and biological mechanisms that potentially drive population changes in both predators and their prey. The eastern Bering Sea shelf, among the most productive marine ecosystems in the world, has undergone significant restructuring in recent decades that is likely to continue in light of anticipated climatic change.

Heather Renner, U.S. Fish & Wildlife Service (USFWS) Alaska Maritime National Wildlife Refuge (NWR)
Brie Drummond, USFWS Alaska Maritime NWR
John Warzybok, USFWS Alaska Maritime NWR
Vernon Byrd, USFWS Alaska Maritime NWR (retired)

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Heather Renner

Kittiwake nesting habitat at the Pribilof Islands.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Do Subsistence Harvests Reflect Ocean Ecology?

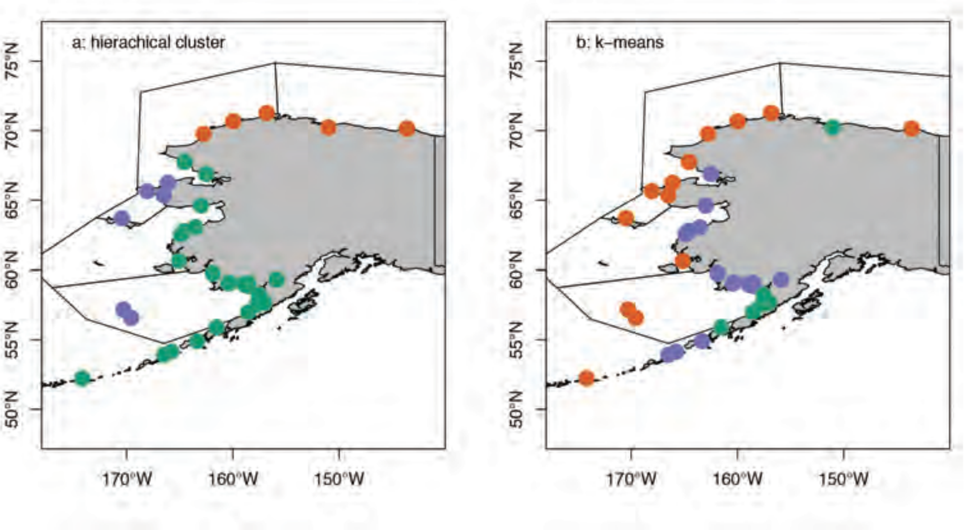
WHAT REGIONAL PATTERNS OF HUNTING AND FISHING REVEAL

When Alaska's coastal residents hunt and fish they, in effect, sample their local environment. We wanted to know what the patterns of subsistence harvests could tell us about ecological patterns in the environment, and also whether those patterns revealed any cultural preferences for certain types of foods. We looked at 35 communities along the coasts of the Bering, Chukchi, and Beaufort Seas. We found that the patterns of local harvests appear to follow biological, oceanographic, and geographic patterns, with the precise patterns depending on the type of analysis (Figure 1). These results suggest that subsistence harvests are samples of the local environment, indicating patterns of regional ecology, physical settings, or other influences on what people harvest. Further studies of harvest levels could reveal patterns over time, reflecting environmental change.

We also divided the villages into six regions and compared the regions to see which regions were most closely related. Not surprisingly, geography dominated the result (Figure 2). Interestingly, the northern Bering Sea aligned more closely

continued on page 2

Fig. 1



Villages (dots) shown in the same color share similar subsistence harvest practices. The variance between (a) and (b) reflects two different cluster analysis approaches. Both analyses show east-west divisions, which appear to follow patterns of ocean currents and species migrations. The left-hand figure (a) also separates North Slope communities, likely reflecting high seal and whale harvests in the area. In the right-hand figure (b), the green dot on the North Slope is Nuiqsut, which is located on the Colville River and has similarities with communities on the Alaska Peninsula that also harvest a mix of fish and marine mammals.

The Big Picture

Our analysis of the relationship between ecological patterns and subsistence patterns is one of many analyses that emerged from all the interactions among researchers throughout the Bering Sea Project. The cluster analysis of subsistence harvest data helps to connect the characteristics of the ecosystem to human interaction with the Bering Sea (and neighboring seas). It is exciting to see that different approaches to studying the ecosystem produce similar pictures of what is happening. This increases our confidence that we are correctly identifying patterns, and also reinforces the idea that ecosystem patterns matter to people who live on the islands and coast of the Bering Sea.

A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

with the Chukchi and Beaufort than with the central and southern Bering Sea. This differs from an analysis of marine ecology done for the same region, but is not surprising given the migration routes of bowhead whales and walrus, which are popular subsistence resources in the northern Bering Sea as well as along the Chukchi and Beaufort coasts.

How We Did It

We started with subsistence harvest survey results compiled by the Alaska Department of Fish and Game. These covered 35 communities in the region. Because some communities had more than one year of data, we had a total of 53 harvest surveys from 1964 to 2009. The degree of detail about the harvest varied from study to study, with more recent studies typically identifying harvests by species (e.g., sockeye salmon, or king eider), rather than by larger group (e.g., salmon, or eiders). For the purpose of establishing a consistent body of data to work with, we had to sacrifice some level of detail and lump some species together. We then conducted the cluster analyses at the village and regional levels to see what patterns emerged.

Why We Did It

An earlier analysis of marine ecology data spurred us to wonder how subsistence harvest patterns compared with the underlying ecological patterns across the same region. While we recognized that hunters and fishers have to rely on what is available, we wondered if other factors might also affect harvest patterns. In addition to satisfying our curiosity, we hoped that the results might shed light on whether subsistence harvest characteristics could be used as indicators of the condition of the ecosystem. Further studies looking at patterns over time would be useful, but at the moment we do not have enough studies in the same villages at different times to do that analysis.

Martin Renner, Tern Again Consulting
Henry Huntington

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2

Communities were grouped into six oceanographic regions, and the results were analyzed to see how similar the subsistence harvests were to one another. The farther left the bar connecting two regions is on the above diagram, the more closely their harvests resemble one another. The Peninsula, AI (Alaska Peninsula and Aleutian Islands) group is most similar to the Southern Bering Sea group. These two are the most similar of any pair of groups. These two are also fairly similar to the Central Bering Sea group. These three, on top, have relatively little in common with the three on the bottom. The Beaufort Sea group and the Chukchi Sea group are closely related, and have some features in common with the Northern Bering Sea group, although this link is not as close.


Henry P. Huntington

Subsistence harvests, such as the variety of foods seen here at a community feast in Wainwright, reflect the ecology of the local area. In this picture, maktak *(bowhead whale skin and blubber) fills the bowls in the foreground, with a variety of fishes, marine mammal meats, soups, and other delicacies behind.*

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Documenting Nelson Island Natural and Cultural History

CAPTURING A WEALTH OF ANCIENT KNOWLEDGE

Between 2006 and 2010, the Calista Elders Council (CEC), the primary research organization for Southwest Alaska, worked with elders and community members from five Nelson Island communities on the Bering Sea coast to document the natural and cultural history of their homeland.

How We Did It

CEC staff traveled with elders out on the land to document historic sites and landscape features on and around Nelson Island (Figure 1). CEC staff also hosted a number of topic-specific gatherings, two- and three-day meetings with elder experts devoted to a single topic, as an effective means of both documenting traditions and addressing contemporary scientific concerns. Unlike interviews, during which elders answer questions posed by those who often do not already hold the knowledge they seek, gatherings (like academic symposia) encourage elders to speak among their peers at the highest level (Figure 2).

Fig. 1

Ann Feinup-Riordan

Simeon Agnus points out a land feature near Arayakcaaq at the mouth of the Qalvinraaq River, July 2007. Michael John sits to his right and Theresa Abraham to his left.

The Big Picture

Coastal communities throughout Alaska, as elsewhere, are undergoing profound environmental, socioeconomic, and cultural changes related to their reliance on marine ecosystems and, increasingly, a global economy. Social scientists, as well as community members, increasingly seek to understand community vulnerability and sustainability. To do so, it is not sufficient to say that changes are taking place. We need to understand how community members interpret these changes--not just what is occurring but why people believe it to be so. CEC's collaborative approach, grounded in community initiatives and local elder gatherings, is a powerful tool that can simultaneously help natural and social scientists understand the unique cultural perspectives that underlie the actions and reactions of coastal residents, and give voice to community understandings of the world in which they live.

Work with Nelson Islanders resulted in two major publications. ***Ellavut*/Our Yup'ik World and Weather: Continuity and Change on the Bering Sea Coast** (Fienup-Riordan and Rearden, 2012) is a 450-page ethnography documenting the *qanruyutet* (oral instructions) that continue to guide Yup'ik interactions with *ella*—translated variously as weather, world, universe, and awareness. The book's ten chapters reflect gathering topics, including weather, land, lakes and

continued on page 2

NELSON ISLAND NATURAL AND CULTURAL KNOWLEDGE PROJECT
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

Fig. 2

Elders and youth discuss place names during a CEC gathering in Chefornak community hall, March 2007.

rivers, ocean, snow, ice, survival, and environmental change (Figure 3).

Our project also produced the bilingual book ***Qaluyaarmiuni Nunamtenek Qanemciput*/ Our Nelson Island Stories: Meanings of Place on the Bering Sea Coast**, winner of a 2012 American Book Award. Elders actively support the documentation and sharing of traditional knowledge, which all view as possessing continued value in the world today (Figure 4).

Community members have embraced the idea of using the web to share information gathered during the Bering Sea Project. In collaboration with National Center for Atmospheric Research (NCAR), Earth Observing Laboratory, CEC has developed a place-based website including the location of over 400 historic sites and geographic features, as well as oral accounts relating directly to over 100 sites. Community members voted unanimously for open access to their site, which can be viewed at http://mapserver.eol.ucar.edu/best.

Expanding on our Nelson Island project, CEC is presently working with ELOKA (Exchange of Local Observations and Knowledge in the Arctic) to link separate mapping efforts in Bering Sea coastal communities into a comprehensive map web service covering 200 miles of coastline and over 6,000 place names. Like the NCAR site, the new site—http://eloka-arctic.org/communities/yupik/—has the capacity to display a wide variety of information (audio, video, text, and photographic), and will serve as an invaluable resource for the region, both educational and capacity building, for years to come.

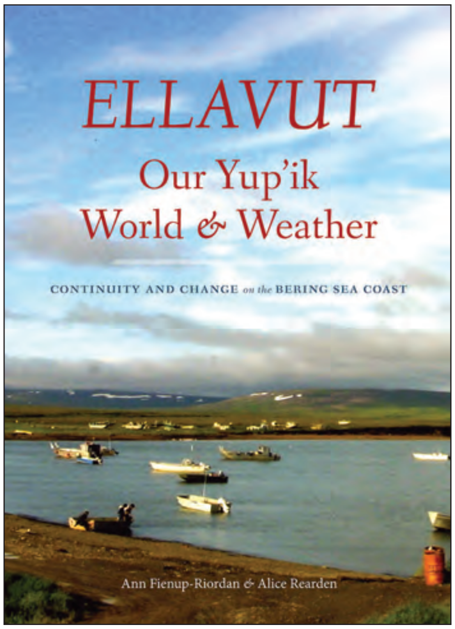
Why We Did It

Nelson Islanders express an urgent need to document their unique natural and cultural history. Many recognize that such documentation must happen in the near future or not at all. Although there will always be elders, the present generation of elder experts are the last to have received a traditional education in the *qasgi* (communal men's house) before the advent of organized religion and formal education. Elders were the primary teachers in the past. Venues to share their knowledge have drastically declined, and contemporary elders actively seek arenas to share their knowledge. Our project provided a unique opportunity for elders, community members, scientists, and local organizations to work together toward this common goal, enriching lives locally while at the same time sharing knowledge globally.

Ann Fienup-Riordan, Calista Elders Council (CEC)
Mark John, CEC
Alice Rearden, CEC

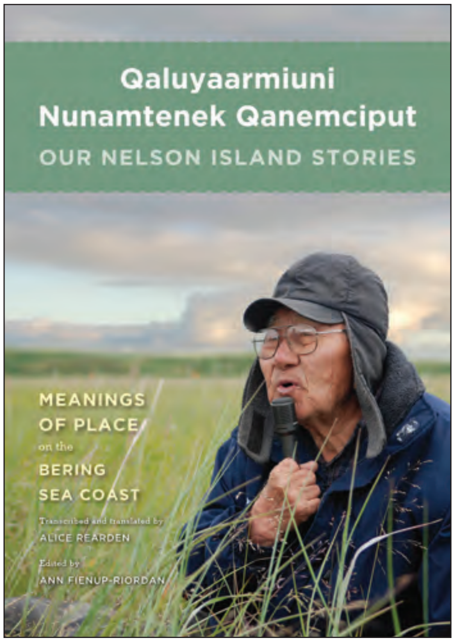
The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 3



Ellavut/*Our Yup'ik World and Weather: Continuity and Change on the Bering Sea Coast* *by Ann Fienup-Riordan and Alice Rearden.*

Fig. 4



Qaluyaarmiuni Nunamtenek Qanemciput/ *Our Nelson Island Stories: Meanings of Place on the Bering Sea Coast* *edited by Ann Fienup-Riordan, with translations by Alice Rearden.*

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Synergies Between Traditional and Western Environmental Knowledge

LINKING LOCAL AND GLOBAL

Between 2006 and 2010, the Calista Elders Council (CEC), the primary research organization for Southwest Alaska, worked with elders and community members from five Nelson Island communities on the Bering Sea coast to document the natural and cultural history of their homeland.

The last 60 years has seen dramatic change in the way Nelson Islanders inhabit their land. Perhaps most significant is the concentration of people into five permanent villages and the abandonment of hundreds of small camps and settlements that were still vibrant through the 1940s. These five villages—ranging in population sizes from 250 to 600—are small by modern standards, but huge compared to the tiny settlements of the past.

As people gather closer together on and around Nelson Island, the island's resources, although still abundant, are more distant. People still harvest from the fishing sites their parents used, but at a cost many find difficult to afford. Now men often travel miles, either by gasoline-hungry snowmobile or skiff, to set their nets and traps.

How We Did It

We interviewed Nelson Islanders to learn their unique, nearshore perspective on the Bering Sea. While oceanographers attempt a comprehensive understanding of the ocean, Yup'ik hunters are most concerned with surface features of the water and ice cover because of their impact on hunting success and safety of travel. Yet, coastal Yup'ik residents also see the ocean as an integral part of ella, a word they translate as weather, world, universe, or awareness, depending on context.

In the many warnings elders give of a dangerous and unpredictable ocean, they also identify key research problems. One example is connecting the response of the nearshore ice regime to ocean swells and tides. Yup'ik people have many words describing the appearance and response of ice to currents and winds. One opportunity for western science/traditional knowledge synergy could be to start with communication that enables sharing such insights and knowledge, followed by focused research partnerships to study the linkage of wind, wave, and ice dynamics.

continued on page 2

The Big Picture

The emerging question that concerns both Yup'ik and non-Yup'ik ocean observers is: How can we link local observations with large-scale environmental issues? Our oceans are now being monitored. If we add to this a greater understanding of the seas immediately offshore, the contrasting scale of global versus local can be bridged. How do we make this potential integration a reality? We can make a start by listening to Yup'ik community members, engaging those whose understanding of the ocean is not only useful but represents a unique worldview. They have long accepted personal responsibility for changes in their homeland. They lead by example.

Fig. 1

Ice mixed with mud on the north shore of Toksook Bay, May 2008.

NELSON ISLAND NATURAL AND CULTURAL KNOWLEDGE PROJECT
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

Fig. 2

Visiting officials, including Senator Mark Begich, inspect the eroding shoreline at Newtok, spring 2010.

Another opportunity for collaboration is provided by meteorologist Uma Bhatt who used satellite images to demonstrate the links between diminishing Arctic sea ice and changes in the Arctic terrestrial ecosystems. She and her colleagues found that areas in the High Arctic have experienced the largest changes, with some exceptions over land regions along the eastern Bering. In discussions with Bhatt, elders pointed out both a decline in tundra berry production and the timing of the harvest in recent years, which they associate with a decrease in fall rain and snow cover. Winds during the growing season were another factor. These observations point to the need to look at changes in wind and precipitation, as well as sea ice cover, to explain changes in coastal ecosystems.

Elders also shared valuable observations about sediment-laden ice--a common characteristic of the shallow, muddy coastal environment (Figure 1). Sea ice scientist Hajo Eicken notes that while coastal erosion is often attributed to a lack of sea ice, in fact sea ice is the most effective mover of sediments in waters with seasonal ice cover. How the ice interacts with the coast is not well understood and cannot be captured by satellites. Local observers recording locations of dirty ice can help with modeling sediment transport by ice.

The rise of sea level and related effects of increased fall storm surges are of particular concern, both to ocean scientists and coastal residents. Elders' long-term observations of these changes may be particularly valuable. The village of Newtok, 10 feet above sea level, was established in 1950 on the low-lying tundra north of Nelson Island. Men chose the site because it was accessible to barges bringing in lumber for the new school. Despite Newtok's marshy location, it doubled in size to 350 today. At the same time Newtok was growing, the land was sinking and eroding at an alarming rate (Figure 2). A move to relocate the village to a bedrock site on Nelson Island is already underway.

Why We Did It

Yup'ik coastal residents of all ages are concerned by the unprecedented changes in climate and ecology they are witnessing along the Bering Sea coast, including changes in the ranges and availability of fish, mammals, and birds; coastal erosion; later fall freeze-up and earlier spring breakup; unusual weather patterns; and increased storminess. Community members feel strongly that elders' perspectives on past periods of resource scarcity, storm surges, and unusual ice and weather conditions, as well as their views on ongoing changes in the Bering Sea ecosystem, will be invaluable in preparing them for the future.

Our work with Yup'ik community members has been a major collaborative effort during which we made a serious attempt to co-produce the knowledge we share. Meetings went beyond consultation and cooperation, with mutual sharing of ideas and understandings. These deep collaborations offer powerful alternatives to more conventional research approaches.

Ann Fienup-Riordan, Calista Elders Council (CEC)
Mark John, CEC
Alice Rearden, CEC

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 3

Mark John and Alice Rearden looking over archival photos with Maryann Andrews of Emmonak and Barbara Joe of Alakanuk during an elders' gathering in Anchorage, April 2012.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

The Role of Edgy Phytoplankton in the Bering Sea Ice Environment

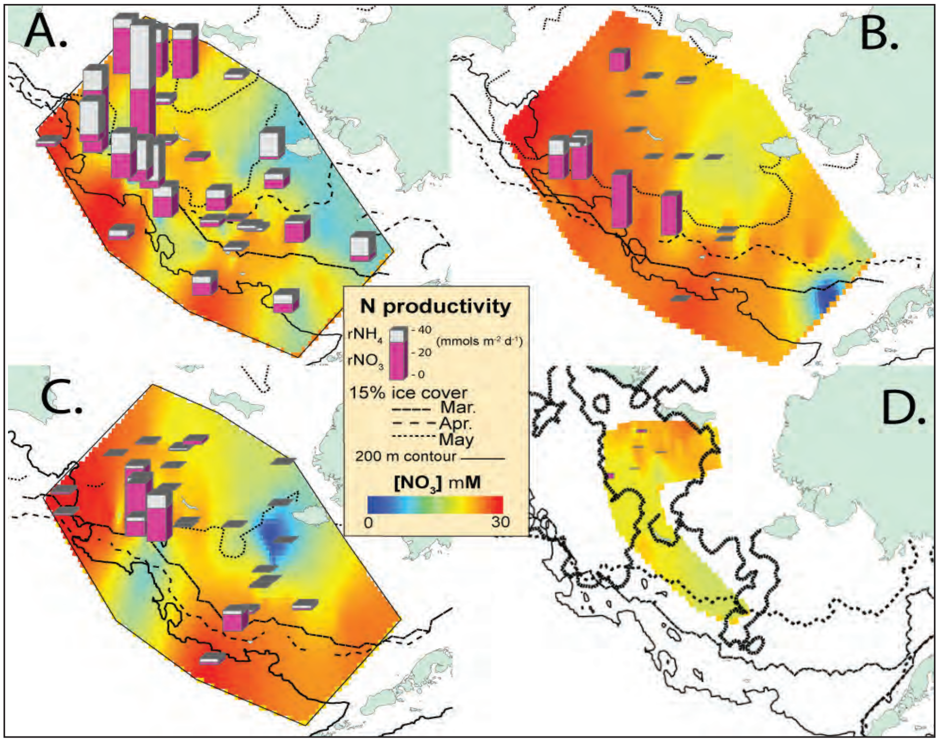
THEY DETERMINE WHO GETS WHAT AND WHERE

This project focused on the growth of phytoplankton, the small photosynthetic organisms that bloom in the spring in high-latitude seas throughout the world. We wondered how sea ice impacts the pattern and intensity of production in the eastern Bering Sea. One of the primary mechanisms we examined was the role of ice in determining the availability of nutrients, particularly nitrogen, required for the growth of all organisms. Some of the more detailed questions we addressed include:

- How does the formation and movement of ice influence the fertility of the region?
- Are the patterns consistent from year-to-year (or at least predictable from sea ice patterns)?
- What is the relative importance of dissolved nitrogen transported onto the shelf from deeper waters, relative to organic nitrogen that is recycled on the shelf?

continued on page 2

Fig. 1



Nitrogen (N) productivity, surface nitrate concentrations, and ice extent in the eastern Bering Sea in A. 2007; B. 2008; C. 2009; and D. 2010. In each panel, the color map represents surface nitrate concentrations (nitrate is the preferred form of nitrogen for phytoplankton growth). Note that the data in 2010 are from a smaller region of the shelf than in the other years. The vertical bars represent nitrogen productivity (a measure of the rate of phytoplankton growth). For each N-productivity bar, purple represents the amount of nitrate productivity and gray represents the amount of ammonium productivity (the two different forms of nitrogen; ammonium is less preferred). The solid line is the 200 m depth. The dashed lines represent the ice extent in March, April and May in each year, and together with the nitrogen productivity rates show the elevated productivity associated with the ice edge on the western shelf.

The Big Picture

Although we know that the extent of sea ice has varied in the eastern Bering Sea, the impact of these variations on the fish, birds, and marine mammals is not well understood. Some of this gap is due to the limited oceanographic sampling of ice that has taken place, particularly in relation to plankton growth and its relationship to nutrient levels. A detailed, mechanistic understanding of how physical environmental changes propagate from the plankton to the populations of upper food web levels is needed to better manage stocks and predict future ecological conditions.

NITROGEN SUPPLY FOR NEW PRODUCTION AND ITS RELATION TO CLIMATIC CONDITIONS ON THE EASTERN BERING SEA SHELF
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

How We Did It

We found that, when it comes to phytoplankton productivity, not all ice edges are created equal—some were associated with dense phytoplankton blooms, but others were not. An exception was the region of the outer shelf, from just north of the Pribilof Islands to beyond Zhemchug Canyon, where we found heavy growths of phytoplankton in each of the four years we sampled it (Figure 1). The ice appears to consistently create good growth conditions here. Also, there was a cross-shelf pattern in the use of nitrogen by phytoplankton in the spring. The outer shelf ice edge blooms were fueled mainly by deep-water nitrogen, while phytoplankton growth in shallower, inshore waters had a much greater dependence on nitrogen that was recycled from previously produced organic matter. This pattern showed up clearly in the phytoplankton incubations we did, as well as in isotopic measurements that were made on the nutrients themselves.

Why We Did It

The fish, birds, and marine mammals that were the focus of the Bering Sea Project depend on the food web, of which they are a part, to supply them with enough resources at appropriate times in their lives. Food for all organisms can be traced to the initial formation of organic material by photosynthetic organisms; in the sea, this mainly comes from phytoplankton. A challenge for marine animals, however, is the extreme variability of phytoplankton production. Phytoplankton are dependent on a combination of oceanographic factors such as wind, ocean currents, and ice that control when and where light and nutrients provide suitable conditions for growth. Phytoplankton growth impacts the upper food web levels in a bottom up fashion, and as the spatial pattern of phytoplankton productivity changes from year-to-year, the fish, birds, and marine mammals must deal with resulting variations in their food supply.

Raymond Sambrotto, Lamont-Doherty Earth Observatory of Columbia University

Daniel Sigman, Princeton University

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

R. Sambrotto

Photograph of the ice edge in the Bering Sea showing the dense growth of algae that turns the bottom of the ice brown. The ice releases these algal cells as it melts, and these contribute to dense phytoplankton blooms at the ice edge.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Protists - Tiny Predators of Phytoplankton

AN AMAZING ARRAY OF ONE-CELLED ORGANISMS FEED IN THE BERING SEA

While copepods are small, about the size of grains of rice, microzooplankton protists are even tinier, less than 200 microns in size, smaller than poppy seeds. How are such miniscule predators able to feed on diatoms, single-celled algae that are often as big, or even bigger, in size than the protist themselves? It turns out that these protists have many, often surprising, ways to prey on diatoms.

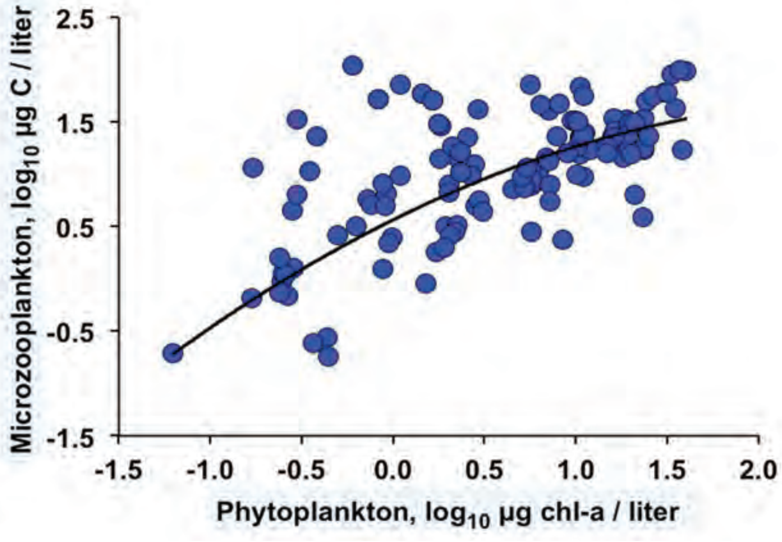
How We Did It

During spring (March-June) Bering Sea cruises in sea ice, we studied the importance of microzooplankton protists as consumers of algae, predominately diatoms, in the Bering Sea. Experiments were done in on-deck incubators to measure growth of algae in seawater with and without the presence of microzooplankton predators. The difference in algal growth, measured by change in amount of chlorophyll during the incubations, showed how much algal production was eaten by the microzooplankton. Using a microscope, we inspected water samples that we had preserved at sea to determine the biomass and types of predatory microzooplankton. In these samples, we took photographs of protists that were caught in the act of feeding on diatoms.

The results of the experimental incubations showed that the microzooplankton protists were important consumers of diatoms. We found a positive relationship between the biomass of these predatory protists and phytoplankton stocks as measured by the concentration of chlorophyll in the water (Figure 1). At some sites, we measured a high amount of protist grazing on intense

continued on page 2

Fig. 1



Log-log relationship between biomass of microzooplankton (µg C/liter) and concentration of phytoplankton (µg chl-a/liter) in the Bering Sea during spring (March-June). Chlorophyll ranged from 0.2 to 38 µg/liter, and microzooplankton biomass from 2 to 72 µg C/liter.

The Big Picture

When ocean ecologists say, "all fish is diatom," they mean that the annual blooms of these large, lipid-filled algae support major marine fisheries. Diatoms, which grow both in sea ice and in the water, are known to form the base of food webs in the Bering Sea. Yet, exactly how the production of diatoms moves through the food chain to fish, seabirds, seals, and whales is still debated. The standard concept is that diatoms are eaten by crustacean zooplankton such as copepods and krill, which are then consumed by higher predators. However, this view of a straight-line food chain is giving way to evidence that much of the diatom production is instead consumed by unicellular predators, protists in the microzooplankton.

MESOZOOPLANKTON-MICROBIAL FOOD WEB INTERACTIONS IN A CLIMATICALLY-CHANGING SEA ICE ENVIRONMENT
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

diatom blooms. Our most surprising finding was the varied ways that protists fed on diatoms.

The most common types of protist predators of diatoms were large-sized dinoflagellates. Common species of marine dinoflagellates use only organic materials as a source of food, and make their living by feeding on other cells. Abundant *Gyrodinium* dinoflagellates in the Bering Sea were able to engulf large diatom cells and chains (Figures 2-A, 2-B, 2-C). In some cases, the dinoflagellate cell was so distended to accommodate a long diatom chain that it appeared about to pop (Figure 2-C). Other types of predatory dinoflagellates are encased in rigid armor plates, called a theca. These thecate dinoflagellates cannot change their shape to surround a diatom chain as do their *Gyrodinium* cousins. Instead, the dinoflagellates extrude an amoeba-like blob of protoplasm that attaches to a diatom chain. The protoplasm surrounds the diatoms, and then enzymes are released to digest the algae and slurp the food back into the dinoflagellate cell (Figure 2-D).

Some types of protists feeding on diatoms were unexpected. Shelled amoebae that sucked out the protoplasm of centric diatoms (Figures 3-A, 3-B) were among the most curious predators. In one shipboard experiment, these amoebae dramatically increased in abundance, which showed that they were able to rapidly grow on diatom food. Even smaller protists prey on diatoms by attaching to the silica shell and injecting enzymes to digest the cell contents. Parasitic flagellates have been previously observed preying on centric diatoms during summer in the Bering Sea. Similar flagellates infested chains of pennate diatoms during our spring study (Figure 3-C). We don't yet know how important these diatom parasites are in the Bering Sea; although parasitic flagellates have been reported to crash a diatom bloom in a European coastal system.

Why We Did It

We hope that future studies will discover the true significance of these varied protists as consumers of diatoms, and whether their feeding impact in Bering Sea food webs might dramatically increase as a result of global warming.

Evelyn Sherr, College of Oceanic and Atmospheric Sciences (CEOAS), Oregon State University (OSU)

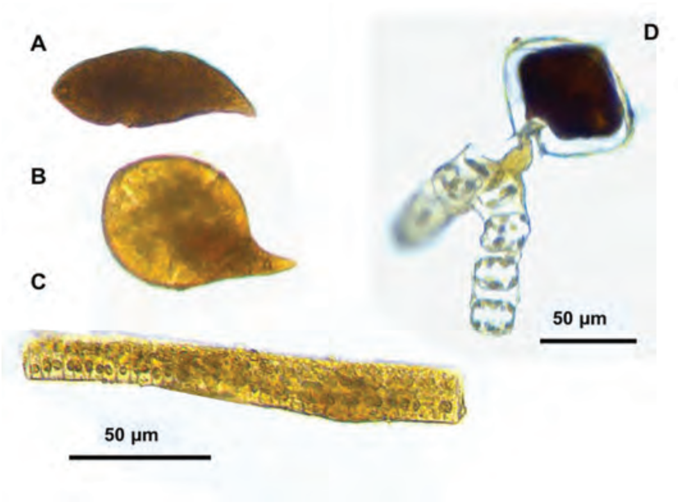
Barry Sherr, CEOAS, OSU

Carin Ashjian, Department of Biology, Woods Hole Oceanographic Institution

Robert Campbell, Graduate School of Oceanography, University of Rhode Island

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Project and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

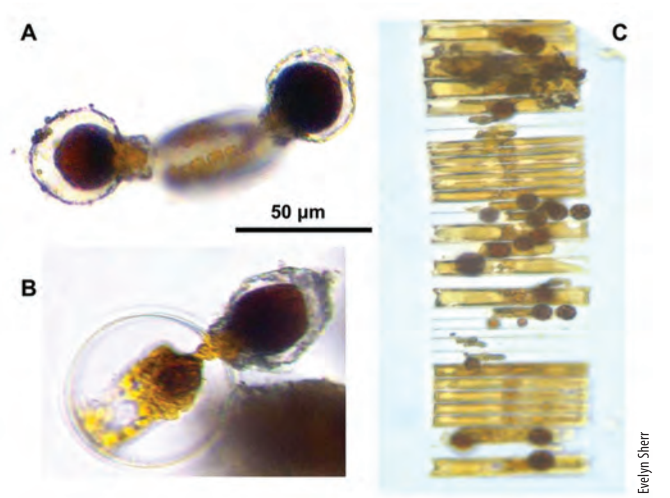
Fig. 2



A, B, C: Evelyn Sherr; D: Celia Ross

Dinoflagellates are well known as predators of large diatom cells and chains. ***A***. Gyrodinium *sp. dinoflagellate without ingested prey.* ***B.*** Gyrodinium *dinoflagellate cell distended with an engulfed single centric diatom cell.* ***C.*** Gyrodinium *dinoflagellate cell grossly distended with an engulfed pennate diatom chain about 40 cells in length.* ***D.*** *Thecate dinoflagellate feeding on a diatom chain by attachment of an extruded blob of protoplasm containing digestive enzymes. The brown color of the cells is from the iodine fixative used in preservation.*

Fig. 3



Evelyn Sherr

Other types of protists found feeding on diatoms included shelled amoebae and parasitic flagellates. ***A***. *Two amoebae attached to one diatom cell.* ***B.*** *Single amoeba feeding on a diatom cell.* ***C.*** Fragillariopsis *diatom chain infested with parasitic flagellates.*

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Organic Matter Mineralization in Bering Sea Sediments

WHAT THE SEAFLOOR TELLS US ABOUT CLIMATE-INDUCED CHANGES

The seafloor is the Bering Sea's recycling center. When food from surface waters hits the bottom, it is consumed by scavengers and bacteria that inhabit the seafloor. The biochemical processes (termed mineralization) that break down this organic carbon are much more complicated and more interesting than one might imagine. Microbial communities use a variety of biochemical processes to oxidize the food that hits the bottom. The oxidative pathways taken by the organic matter likely vary with the rate of food supply to the seafloor. Because much of the organic matter export to the Bering Sea floor occurs during seasonal sea ice melt, a warming climate would be expected to reduce the quantity of organic matter reaching the sediment, and this change could be observed by studying organic matter mineralization processes in Bering Sea sediments.

The most energy-efficient mechanism of organic matter mineralization is aerobic respiration. But, in the absence of dissolved oxygen, microbes use anaerobic respiration with different oxidants to break down organic carbon. The sequence of oxidants that we would expect to observe in Bering Sea sediments in order of decreasing efficiency is oxygen, nitrate, manganese oxide, iron oxide, and sulfate. This sequence produces vertical gradients in these chemicals within the sediment column. The various organic matter mineralization mechanisms follow different chemical reactions and produce different by-products.

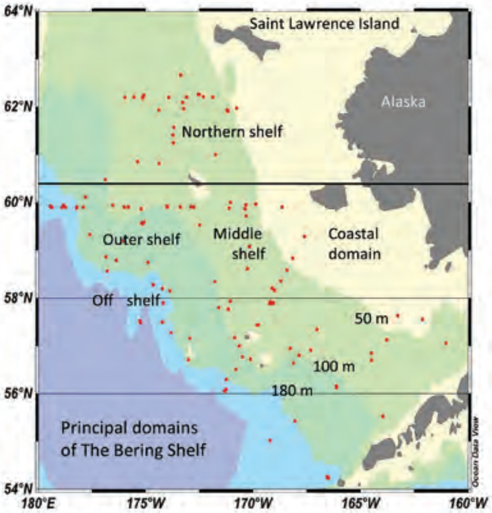
We hypothesized that organic-carbon mineralization pathways would vary with food supply to the seafloor, and this would produce observable regional variation in the organic matter mineralization

continued on page 2

Fig. 1

Deploying a multi-corer.

Fig. 2



Red dots indicate locations of core samples taken from across the eastern Bering Sea over a four-year period.

The Big Picture

Organic matter production fuels the highly productive Bering Sea food web. The amount of organic matter exported to the seafloor varies spatially across the Bering Shelf, and may reflect longer-term changes in productivity related to the seasonal melting of sea ice and the development of nutrient limitation on the shelf. But what happens to this material after it hits the bottom?

We quantified the fate of organic matter in Bering Sea sediments and discovered that the processes vary regionally, reflecting the export of organic matter from the water column. Because sedimentary processes tend to filter out short-term fluctuations, the variation in organic-matter mineralization in the sediments may be a useful indicator of climate-induced changes in ecosystem productivity that fuels the important Bering Sea fishery.

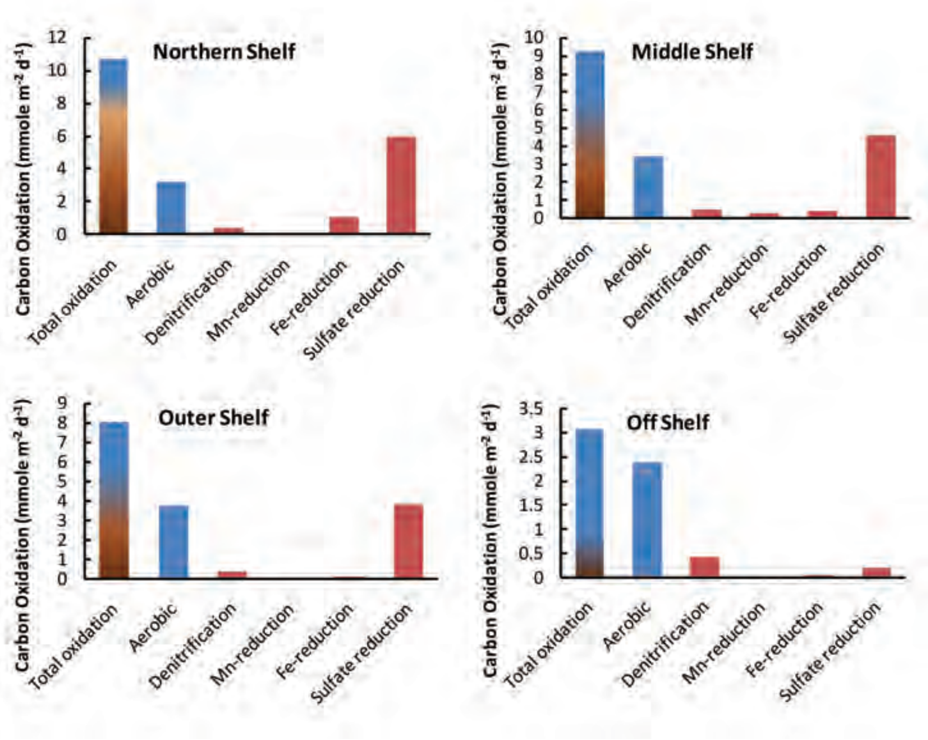
DENITRIFICATION AND GLOBAL CHANGE IN BERING SEA SHELF SEDIMENTS
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

pathways. Specifically, we expected the proportion of organic matter mineralization due to aerobic respiration to increase from north to south on the Bering Shelf, and also increase from onshore to offshore. This pattern parallels independent estimates of organic matter export, which is largest in the northern shelf and drops to the south and offshore. We set out to test this hypothesis in order to better understand how organic matter is recycled in Bering Sea sediments and how it relates to the supply of food from overlying water.

How We Did It

We deployed a hydraulically-damped "multi-corer" (Figure 1) which drops to the bottom, slowly plunges eight sampling tubes into the sediment, carefully withdraws and caps the tubes, and transports the intact section of seafloor back to the ship for analysis and experimentation. We collected sediment cores from approximately 125 locations on the Bering Shelf, slope and rise over four years (Figure 2). We incubated cores on the ship at near in situ temperatures and directly measured the rate of oxygen consumption and nitrogen gas production (to quantify denitrification) in the sediments. We measured the rate of sediment mixing (bioturbation) using the chemical tracer ^{234}Th and used that rate, along with profiles of manganese (Mn) and iron (Fe) oxides, to estimate the rates of Mn and Fe reduction. We also incubated sediment amended with radioactive sulfate to determine the rates of sulfate reduction. These measurements allowed us to determine how sedimentary organic matter was remineralized in different regions of the Bering Sea, and to test our hypothesis regarding its regional variation. Indeed, our results confirmed that food supplied from the overlying water takes different oxidative pathways in different regions of the Bering Sea in a manner that is consistent with its variation in supply from the water column (Figure 3).

Fig. 3



Moving from the Northern Bering Shelf toward the south (that is, toward the middle shelf at similar water depths), and from the middle shelf to deeper water, the relative importance of aerobic respiration increases and anaerobic respiration, especially sulfate reduction, decreases in importance.

Why We Did It

Sedimentary processes tend to reflect average conditions and filter out short-term fluctuations. Processes in overlying water are subject to considerable variation, even at small spatial and temporal scales. Thus, variation in sedimentary processes such as organic matter mineralization may indicate longer-term changes in conditions in the Bering Sea. Our results were consistent with our hypothesis that the proportion of organic matter mineralization due to aerobic respiration would increase from north to south on the Bering Shelf, and also increase from onshore to offshore. This pattern parallels independent estimates of organic matter export. As this ecosystem changes on decadal and longer time scales, these changes may be reflected in organic matter mineralization pathways revealed in the sediment.

David Shull, Department of Environmental Sciences, Western Washington University

Allan Devol, School of Oceanography, University of Washington (UW)

Rachel Horak, School of Oceanography, UW

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Hot Spots in the Bering Sea

24-HOUR DINERS FOR SEABIRDS AND WHALES

If you have to hunt for your food in the cold and stormy Bering Sea, finding predictably dense patches, or persistent "hot spots" of your favorite prey saves you time and energy, and may make the difference between survival and starvation. But what happens if you are a seabird or a fur seal and changes in the ocean make these hot spots less predictable during a time when you have to regularly return to the place where you nurture your young? Would the change matter if you are a migratory whale that is not tied to one place, and is just in Alaska to take advantage of the ocean's summer bounty?

We know these ocean predators often exploit places where small fishes and zooplankton persist in large patches. But does the way these predators hunt, and whether they are tied to a breeding site, affect their ability to respond to these dense patches of prey or changes therein?

How We Did It

At sea, we examined distributions of surface-feeding black-legged kittiwakes (*Rissa tridactyla*) and pursuit-diving thick-billed murres (*Uria lomvia*)) during their summer nesting period when their foraging range is limited. We also looked at free-ranging humpback (*Megaptera novaeangliae*) and fin whales (*Balaenoptera physalus*). We studied the distribution of all four species in relation to two of their key prey: age-1 walleye pollock

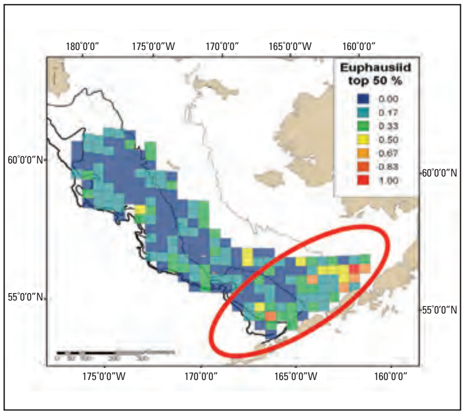
continued on back side

The Big Picture

In Alaska, seabirds, whales, fishes, and plankton are abundant on the Bering Sea shelf and slope, a productive ecosystem supplying food for millions of seabirds and tens of thousands of marine mammals. In this study, we tackled the Bering Sea Project hypothesis that climate and ocean conditions influencing circulation patterns and physical domain boundaries will affect the distribution, frequency and persistence of fronts and other oceanographic features that concentrate prey, and affect the foraging success of marine birds and mammals largely through bottom-up processes.

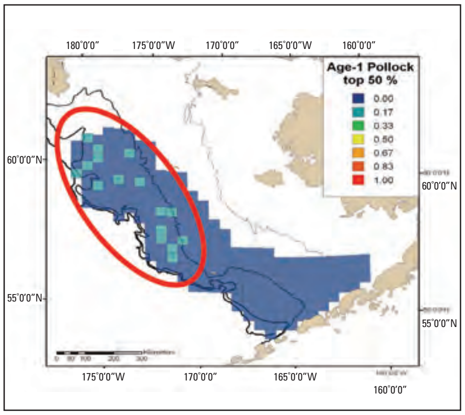
We quantified the distributions of open-ocean prey species and determined that marine predators often associated with areas where these "hot spots of prey" persist at certain times of the year for several years. But we also wanted to determine whether the hunt for food differed among species that were tied to a colony or not, or between animals built to dive for their food versus those that can fly long distances but must feed on the surface. Our conclusion: being tied to a central place matters, as does the way you look for food.

Fig. 1



We found euphausiids all over the place, with persistent hot spots within specific 37 × 37 kilometer blocks

Fig. 2



Age-1 pollock were patchier and their hot spots persisted only on scales greater than 37 kilometers.

TOP PREDATOR HOTSPOT PERSISTENCE
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

(*Theragra chalcogramma*) and euphausiids (*zooplankton of the family Euphausiidae*).

We surveyed the prey once each year during 2004 and 2006-2010, and surveyed the seabirds in 2006-2010 and the whales in 2008 and 2010. We compared the seabird and whale locations to where age-1 pollock and euphausiids were concentrated and considered how long these concentrations were present in time and space on an annual scale. This allowed us to compare this measure of prey persistence among annual surveys.


Alexandra Ravelo

Seabirds, whales and other ocean predators seek out persistent "hot spots" where small fishes and other prey gather in dense patches.

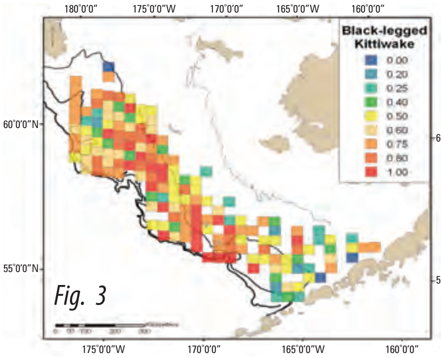


Fig. 3

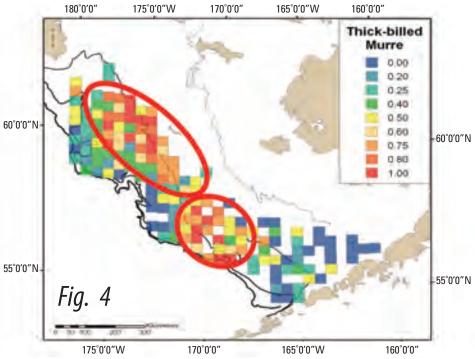


Fig. 4

Both kittiwakes and murres, despite the difference in their feeding style, were consistently associated with age-1 pollock but not consistently with hot spots of euphausiids, even though the euphausiids hot spots were more persistent than those of the small fish. The diving thick-billed murres, which have greater travel costs than kittiwakes, foraged on prey concentrations nearer their island colonies than did the surface-feeding black-legged kittiwakes, which foraged widely.

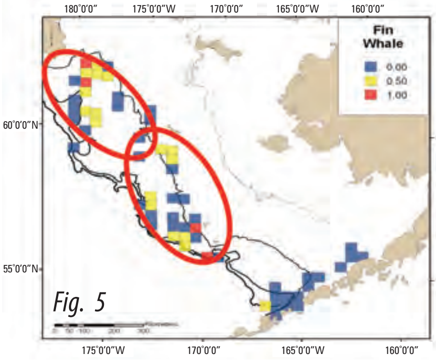


Fig. 5

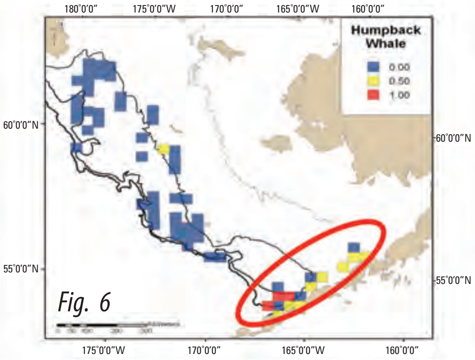


Fig. 6

Humpback and fin whales were not tied to a central place. We found humpback whales only where euphausiids were concentrated and where these concentrations were persistent. We observed fin whales where age-1 pollock were more likely to occur, similar to black-legged kittiwakes and thick-billed murres, but their association with euphausiids was unclear.

Why We Did It

The ability to remember the location of preferred prey is an important part of the foraging behavior of whales, seabirds, and other ocean predators. An important characteristic of these prey concentrations is their persistence in time and space, which allows predators to predict or remember their locations and concentrate search efforts accordingly. Predictable prey locations reduce search time and thus the energetic costs of foraging. Predators tied to a location to incubate and rear their young face the additional challenge of locating prey close enough to their colony to frequently feed their young.

Mike Sigler, NOAA Alaska Fisheries Science Center
Nancy Friday, NOAA National Marine Mammal Laboratory
Kathy Kuletz, US Fish and Wildlife Service
Patrick Ressler, NOAA Alaska Fisheries Science Center
Chris Wilson, NOAA Alaska Fisheries Science Center
Alex Zerbini, NOAA National Marine Mammal Laboratory

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Warm and Cold Years in the Southeastern Bering Sea

WEATHER MATTERS

The Bering Sea is ice-free during summer, but beginning in November or December, sea ice begins to form along the coast. In January and February, strong winds out of the north push the ice southward 1,000 km, covering much of the shelf. Air temperature and the timing and persistence of these “arctic blasts” varies widely from year to year. While there is always ice on the northern shelf in winter and much of spring, the maximum southern extent of the ice can vary by 100s of kilometers between years (Figure 1). In “warm” years, there is little ice in March and April south of latitude 57° 30’, whereas in “cold” years the ice persists in the south for many weeks in early spring.

Sea ice plays an important role in the physics and biology of the eastern Bering Sea. It results in colder spring ocean temperatures, an early ice-associated phytoplankton bloom, a less saline water column and a summer cold pool where temperatures in the bottom water layer remain below 2 °C.

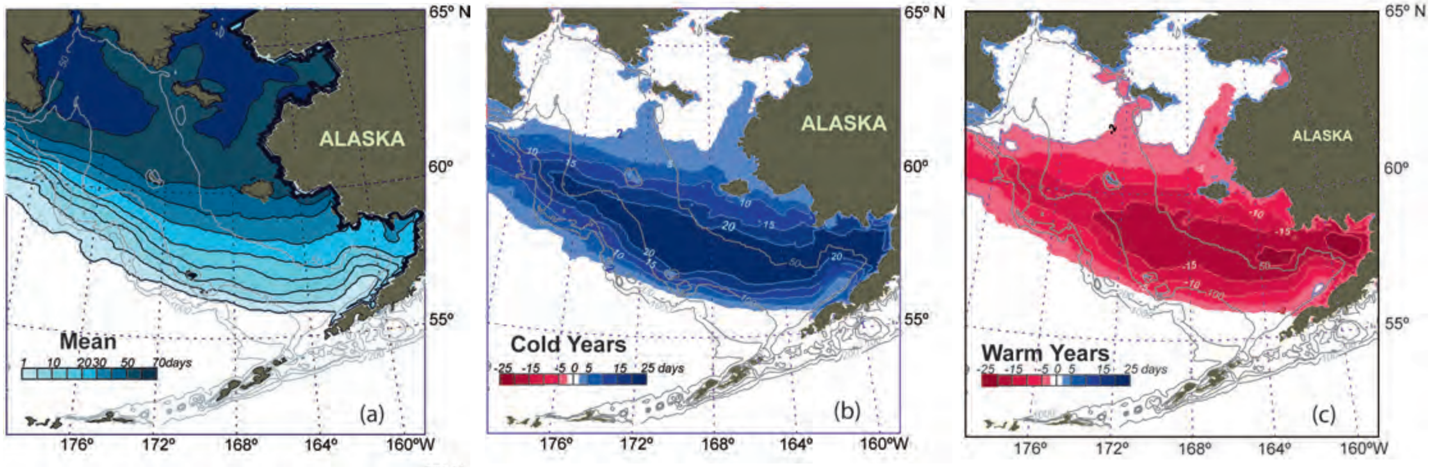
In February 2000, the southeastern Bering Sea entered an almost 6-year period of little ice and “warm” conditions. After a transition year in 2006, extensive sea ice returned to the southern shelf, and these cold conditions

continued on page 2

The Big Picture

The transition between the Arctic and subarctic occurs in the southern Bering Sea, and the boundary between the two is very sensitive to climate changes. Changes in the temporal patterns of variability can also impact this system. Seasonally icy seas, like the Bering Sea, respond differently to changes in ice cover than Arctic seas that presently have year-round ice. Recent multiple consecutive years of warm conditions with less ice in winter and spring yielded fewer large zooplankton, an important prey species in this ecosystem, and led to lower pollock recruitment.

Fig. 1



(A) Average number of days in which sea ice was present in March and April during 2001-2010. The anomalies of sea-ice coverage during March and April during (B) the cold years, 2007-2010, and (C) the warm years, 2001-2005.

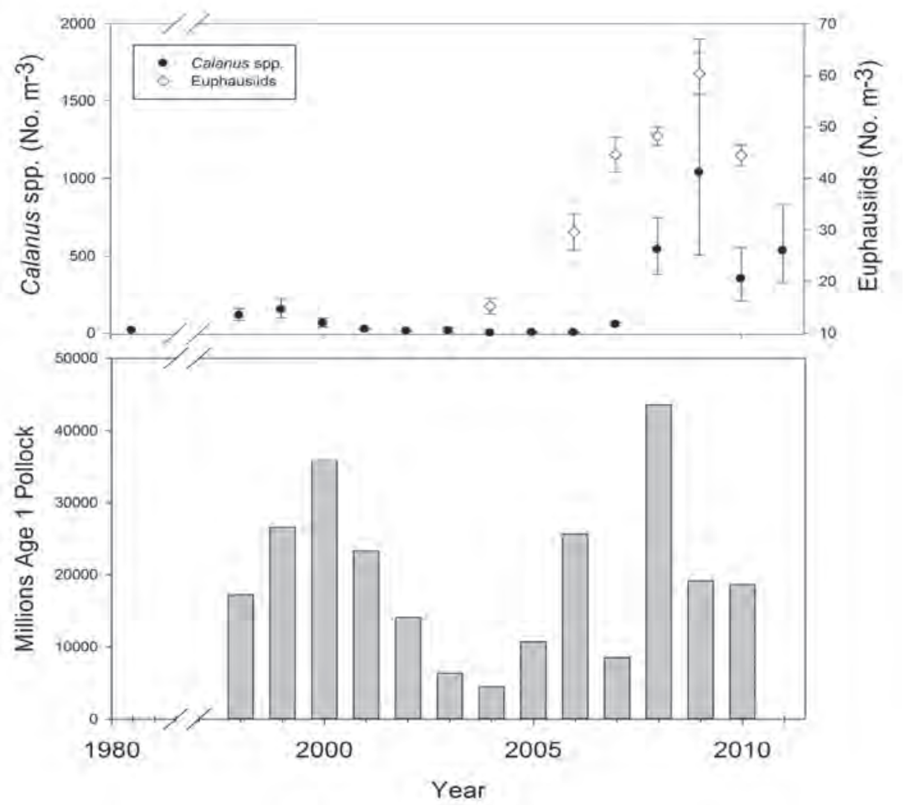
BIOPHYSICAL MOORINGS
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

were still present in 2013. Scientists originally hypothesized that warmer conditions would favor walleye pollock and other fish species that prefer temperatures above 2°C; however, with warmer conditions, there was a sharp decrease in the availability of key prey items for young-of-the-year pollock, limiting the survival of fish during their first winter (Figure 2). An interesting question that remains is "has the Bering Sea shifted from strong year-to-year variability to a multiyear pattern, which is more common in the Gulf of Alaska?" Such a change would have important repercussions on this ecosystem.

How We Did It

We utilized a wide range of data from cruises, moorings, the National Snow and Ice Data Center, and Alaska Fisheries Science Center trawl surveys to examine the relationship between ice in March and April and depth-averaged temperature from long-term mooring on the southeastern shelf, M2. The timing of the spring phytoplankton blooms was also obtained from the chlorophyll fluorescence data on the moorings, showing that when ice was present after mid March on the southern shelf, there was an increase in fluorescence and a decrease in nutrients. Plankton net tows from ships maintaining the moorings provided data on prey availability.

Fig. 2



*Large crustacean prey and year class strength of walleye pollock. (Top) Abundance of copepods (*Calanus *spp) and adult and juvenile euphausiids (krill) sampled during the summer. Copepods were sampled with plankton nets and euphausiid abundance was estimated with acoustics. (Bottom) Estimated number of pollock surviving to age-1 for each year class. Estimates obtained from stock assessment models (Ianelli et al., 2012, Table 1.23).*

Why We Did It

The southern Bering Sea is a rich ecosystem that supports large numbers of marine mammals and seabirds, and provides approximately 40% of the U.S. catch of fish and shellfish. We now know that changes in the weather patterns and ice extent over the southern shelf affect zooplankton abundance and distribution patterns, which in turn impacts the fishes, large baleen whales, and seabirds that feed in these waters. Climate models predict that the southern Bering Sea will become warmer, with reduced sea ice in the next couple of decades. If the warm period (2000-2005) is any indication of how the ecosystem will respond to warming, such a change will strongly affect the existing ecosystem. Understanding how shifts in climate impact this system will help scientists predict who the winners and losers could be, and provide the opportunity to help cushion the impact of the changes on humans who utilize this ecosystem.

Phyllis J. Stabeno, National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory

Jeffrey Napp, NOAA Alaska Fisheries Science Center

Lisa Sheffield Guy, University of Washington Joint Institute for the Study of the Atmosphere and Ocean

Mike Sigler, NOAA Alaska Fisheries Science Center

Literature cited

Ianelli, J., T. Honkalehto, S. Barbeaux, S. Kotwicki, K. Aydin and N. Williamson (2012). Assessment of the walleye pollock stock in the eastern Bering Sea. 2012 North Pacific Groundfish Stock Assessment and Fishery Evaluation Reports for 2013.

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Project and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Summer Microzooplankton in the Bering Sea THEIR SURPRISING ROLE

In spring, large diatom blooms occur in the Bering Sea that supply food for large zooplankton that in turn are food for many small fish, seabirds and whales. In summer, the big diatoms blooms are gone from the surface waters and most of the phytoplankton are too small for zooplankton to eat. What do zooplankton eat in summer in the Bering Sea? We thought that part of the answer might be microzooplankton, which are microscopic, one-celled organisms that eat small phytoplankton. The microzooplankton, although tiny by our standards, are big enough to be captured and ingested by large zooplankton. In fact, many large zooplankton prefer to eat microzooplankton over phytoplankton. Microzooplankton can be an important link between phytoplankton production and higher trophic levels, especially when phytoplankton are scarce or small in size. Our goal was to determine if microzooplankton are important as a potential food source for large zooplankton in summer.

How We Did It

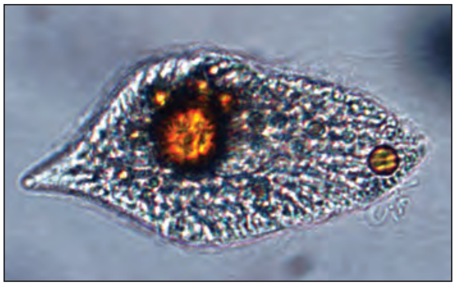
We went on month-long cruises in summers of 2008, 2009 and 2010 on which we collected water from different depths with Niskin bottles on a a conductivity, temperature, and depth recorder (CTD) rosette (Figure 1). We used the water to

continued on page 2

Fig. 1

Diane Stoecker

Kristen Blattner removes water from a Niskin bottle on the CTD rosette to determine the quantity of microzooplankton.



Diane Stoecker

Microzooplankton include heterotrophic dinoflagellates, such as this Gyrodinium *with ingested prey.*

The Big Picture

We addressed a gap in knowledge of planktonic food webs in the Bering Sea by examining the role of microzooplankton in summer. We found that microzooplankton were very abundant, particularly in shelf waters, and were a major food source available to larger zooplankton. By examining differences in the role of microzooplankton in regions with different physical forcing (i.e., stratification, mixing, and other oceanographic features) and comparing the role of microzooplankton among years, our study specifically addressed the Bering Sea Project hypothesis that "climate-induced changes in physical forcing will modify the availability and partitioning of food for all trophic levels through bottom-up processes." We found that there are important regional differences in the Eastern Bering Sea, with differences in physical forcing affecting the role of microzooplankton. Comparison of our data from three "cold" years to previously collected data from "warm" years show that microzooplankton are an important component of planktonic food webs in the Eastern Bering Sea in both "warm" and "cold" years.

A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

Fig. 2

John Dolan

Microzooplankton include planktonic ciliates, such as this tintinnid from the Bering Sea.

conduct grazing experiments at sea to estimate the amount of phytoplankton eaten by microzooplankton. We did this by incubating the water in flowing seawater incubators on-deck and measuring changes in chlorophyll *a* (green plant pigment that is a proxy for phytoplankton biomass) in bottles with different concentrations of microzooplankton. Some of the water we preserved and brought back to our laboratory at the University of Maryland Center for Environmental Science, so that we could examine it under a microscope. We used our microscopic observations to identify, count, and estimate the biomass of microzooplankton.

Why We Did It

We set out to determine the abundance and biomass of microzooplankton, and to compare their biomass to phytoplankton biomass so that we would know how important they were relative to phytoplankton as a potential food source for zooplankton. We also wanted to determine how much of the phytoplankton production was eaten by microzooplankton. Although phytoplankton stocks are low in summer, there are "hotspots" along the shelf edge and near the Pribilof Islands where there are more phytoplankton than on most of the shelf. We wanted to determine if the importance of microzooplankton was greater in areas with lower phytoplankton stocks than in areas with higher phytoplankton stocks.

We observed that in summer the presence of microzooplankton was very important in surface waters over much of the Bering Sea Shelf because they dominated the size class of plankton that is the right size food for large zooplankton. On the middle and inner shelf, where phytoplankton are scarce in summer, microzooplankton biomass was higher than phytoplankton biomass! This was a bit puzzling, because in food webs, there is usually a higher biomass of "grass" than "cows." Part of the answer to this puzzle is that many of the microzooplankton were large, green ciliates (Figure 2) that are grazers on small phytoplankton but are photosynthetic and can also produce their own food. We found that in surface waters on the middle shelf, ciliates sometimes contributed over 50% of the chlorophyll!

Microzooplankton were also important as grazers on phytoplankton; they consumed almost all of the daily phytoplankton production on the middle and inner shelf. Although phytoplankton were generally low in abundance in surface waters on the shelf, on the northern shelf there were high concentrations of phytoplankton at depth. These deep concentrations of phytoplankton were probably remains of the spring bloom that had sunk out of the surface waters. Microzooplankton are an important component in these deep, cold layers of plankton that may serve as "refrigerators full of food" for zooplankton in summer, forming an important link in food webs that support higher trophic levels in summer on the Eastern Bering Sea Shelf.

Diane Stoecker, University of Maryland Center for Environmental Science, Horn Point Laboratory

Alison Weigel, University of Maryland Center for Environmental Science

Kristen Blattner, University of Maryland Center for Environmental Science

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Diane Stoecker

A thecate heterotrophic dinoflagellate, also a member of the microzooplankton.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

A Lasting Legacy of the Bering Sea Project

ARCHIVAL AND PRESERVATION OF THE PROJECT DATA FOR CURRENT AND FUTURE RESEARCH

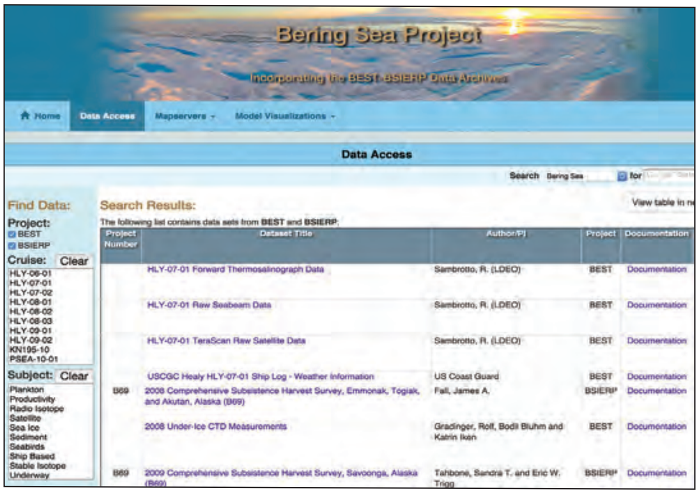
In a collaboration called the "Bering Sea Project," the National Science Foundation (NSF) supported the Bering Ecosystem Study (BEST) and the North Pacific Research Board (NPRB) developed and supported the Bering Sea Integrated Ecosystem Research Program (BSIERP) to address changes in this critical marine ecosystem. More than 100 scientists engaged in field data collection, original research and ecosystem modeling during the Bering Sea Project to link climate, physical oceanography, plankton, fishes, seabirds, marine mammals, humans, traditional knowledge and economic outcomes. The resulting 356 datasets established a new paradigm for critical information needed to answer key questions about these changes. The Earth Observing Laboratory (EOL) of the National Center for Atmospheric Research (NCAR) brought 25 years of experience to provide all facets of data management support to the Bering Sea Project.

How We Did It

The data management support for the BEST and BSIERP Programs developed independently during the initial years of data collection. Later the support was consolidated, but the principles of support for investigator datasets remained firm as NSF and NPRB worked together to develop a single archive at EOL for the Bering Sea Project. The Bering Sea Data Archive at http://beringsea.eol.ucar.edu (Figure 1) is the single source for all data from this collaborative effort.

continued on page 2

Fig. 1



Search Results:

The following list contains data sets from **BEST** and **BSIERP**:

Project Number	Dataset Title	Author/PI	Project	Documentation
	HLY-07-01 Forward Thermosalinograph Data	Sambrotto, R. (LDEO)	BEST	Documentation
	HLY-07-01 Raw Seabeam Data	Sambrotto, R. (LDEO)	BEST	Documentation
	HLY-07-01 TeraScan Raw Satellite Data	Sambrotto, R. (LDEO)	BEST	Documentation
	USCGC Healy HLY-07-01 Ship Log - Weather Information	US Coast Guard	BEST	Documentation
B69	2008 Comprehensive Subsistence Harvest Survey, Emmonak, Togiak, and Akutan, Alaska (B69)	Fall, James A.	BSIERP	Documentation
	2008 Under-Ice CTD Measurements	Gradinger, Rolf, Bodil Bluhm and Katrin Iken	BEST	Documentation
B69	2009 Comprehensive Subsistence Harvest Survey, Savoonga, Alaska (B69)	Tahbone, Sandra T. and Eric W. Trigg	BSIERP	Documentation

Bering Sea Project Database example entry. It is possible to search 356 combined BEST and BSIERP datasets by project, cruise and science subject. The resulting table provides a direct link to the dataset and documentation for easy download and access.

The Big Picture

The Bering Sea project data archive developed by and housed at the NCAR/EOL will remain the long-term legacy of the Bering Sea Project. More than 100 investigators deployed during different seasons to document the ecosystem and related oceanography and meteorology of the region. Not only was the volume of available data from the region significantly increased during the Bering Sea Project, the data coverage in space and time extended into previously unsampled domains. While much has been learned from the initial and ongoing analyses of these data, they will continue to provide fodder for future analyses in response to unanticipated and serendipitous observations, to serve as model forcing and validation resources, and to define baselines against which future ecosystem changes may be evaluated. EOL developed the archive, uploaded datasets and documentation from users, provided web access to the data and has assumed long-term stewardship of this unique data archive for the benefit of science and society as they seek to better understand the Bering Sea ecosystem.

BERING SEA PROJECT DATA MANAGEMENT
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

Our comprehensive data management strategy included early involvement with the science team to determine their requirements and establish priorities based on available resources, resulting in a clear specification for metadata and documentation to accompany all datasets. The easily accessible database cross-references each unique investigator dataset (Figure 1). Researchers can peruse data inventory through a search tool to access data listed in tables by cruise, subject category or investigator's name. Ongoing maintenance of the metadata assures its long-term accuracy, thus allowing future consistent access and data discovery.

EOL provided specialized support to the 10 NSF-sponsored Bering Sea Project cruises on multiple ships (2007-2010) that included implementation of a BEST Project Field Catalog (Figure 2) for use aboard ship. It allowed real-time documentation of data collection to be uploaded by the science team, heads-up displays of current ship track and position, all ship–based sampling stations from the current or any previous cruise (critical in the repeat location sampling strategy used during the project) and any operational products (e.g. satellite, sea ice edge, currents) used for real time cruise track selection. The BEST Field Catalogs for each cruise remain active via the EOL website for future reference.

EOL also worked closely with a Bering Sea Project ethnographer to develop a Geographic Information System (Figure 3) user tool for displaying detailed data and information collected during the Nelson Island project, including place names and links to stories and photos by location.

Why We Did It

After all of the data collection is a distant memory, there will be a single, unified data legacy for the Bering Sea Project. The 356 datasets will help mark the extraordinary efforts and accomplishments of 100 investigators over more than six years. The analyses of those datasets are already revealing important information about the make-up of this unique ecosystem in the Bering Sea. Ongoing analysis efforts are enhanced by a high-quality data archive that assures consistent access to all of the valuable data. EOL provides the long-term stewardship of the Bering Sea Project data using the established capabilities of the NCAR archive system.

Don Stott, Earth Observing Laboratory, National Center for Atmospheric Research

Janet Scannell, Earth Observing Laboratory, National Center for Atmospheric Research

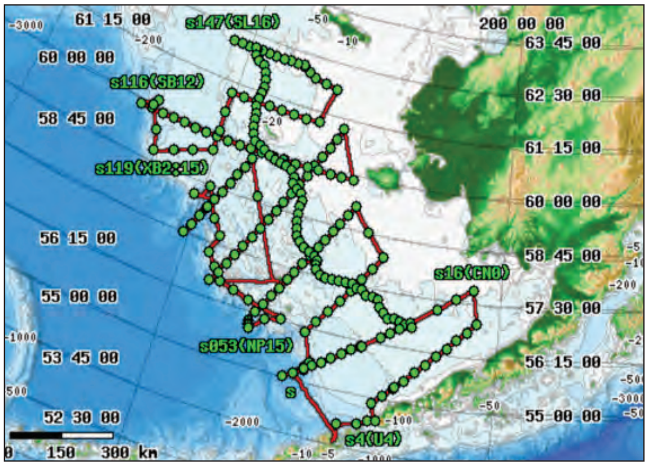
James Moore, Earth Observing Laboratory, National Center for Atmospheric Research

Steve Williams, Earth Observing Laboratory, National Center for Atmospheric Research

Amanda Orin, Earth Observing Laboratory, National Center for Atmospheric Research

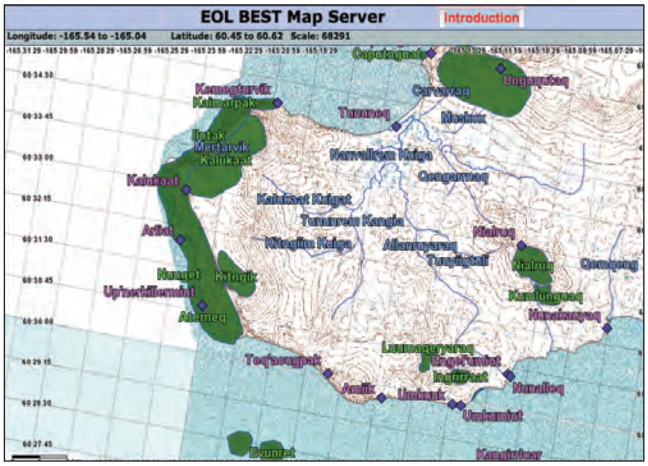
The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



The EOL BEST Field Catalog deployed on various ships during 10 cruises from 2007-10. Image shown is the cruise track and stations during the R/V Knorr *summer 2009 cruise ((KN195-10). The catalog also provides operational and research data products, station reports and preliminary research analysis products.*

Fig. 3



EOL-developed LTK GIS mapserver interface for Nelson Island. The image here shows a sampling of the place names acquired during the multi-year study. Each place name is color or symbol coded to identify the specific type of site (e.g. burial, hunting, historical). Each site is an active link to related photos and stories about that specific location.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

A Moveable Feast

SEABIRDS TRACK PREY IN THE SOUTHEAST BERING SEA

Seabirds have to find enough food to raise their chicks at the colony in summer, which restricts how far they can search for food. Afterwards, as they prepare for migration and winter survival, birds can more freely search for prey. The breeding and post-breeding periods thus pose different challenges for seabirds. We looked at seabird response to prey distribution in summer and fall, as an indication of how seabirds might respond to changes occurring in the Bering Sea.

How We Did It

We measured the abundance and distribution of predators and prey in the southeast Bering Sea in summer and fall (2008–2010) by conducting seabird surveys from the same fisheries research vessels used to estimate krill and fish abundance.

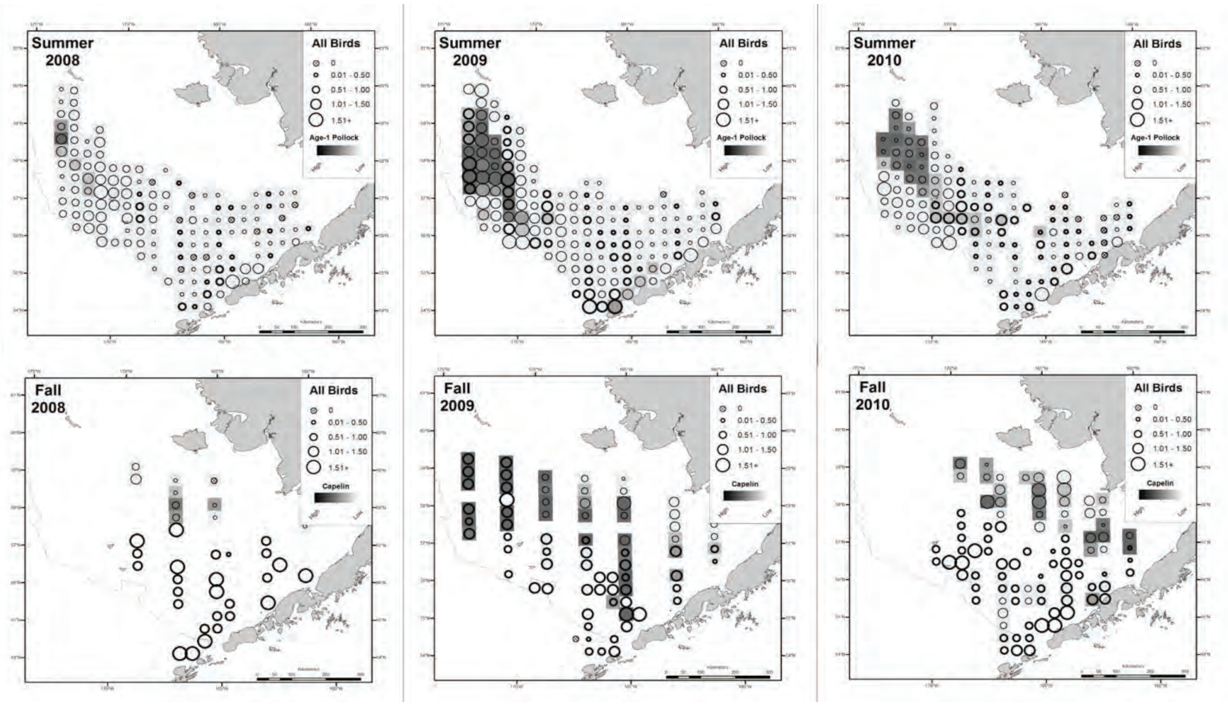
In summer, seabirds tended to be 'clustered' and occurred near breeding colonies, where they foraged primarily on the outer shelf. In fall, seabirds were more abundant overall, with a

continued on page 2

The Big Picture

Few studies of seabirds in Alaska have occurred outside of summer months. We found that seabirds appeared to be responding to broad-scale changes in seasonal prey distribution, with a greater dependence on forage fish over the middle and inner shelf in fall. Fall may be as crucial as summer to the health of seabird populations, and changes in forage fish distribution in fall due to climate change could be bad for seabirds. At the least, it could affect the species composition of the seabird community and where or how much seabirds aggregate. Understanding mechanisms affecting seabird-prey relationships is critical to ecosystem-based management in a changing climate.

Fig. 1



Distribution of seabirds and key prey in summer (top panels) and fall (bottom panels) in the study years 2008-2010. Seabird numbers are represented by scaled circles, and prey density is shown as light to dark shading.

SEABIRD BROAD-SCALE DISTRIBUTION
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

USFWS

Millions of short-tailed shearwaters sometimes aggregate at Unimak Pass in July, along with humpback whales.

Sophie Webb

A newly fledged black-legged kittiwake.

Luke DeCicco

Age-0 juvenile walleye pollock, a key prey for seabirds in the Bering Sea.

greater variety of species, as southern migrants moved in for the feast of available fish and euphausiids (also known as krill). In addition, newly fledged juveniles joined adults at sea. Seabirds were also less clustered in fall, and they dispersed throughout the outer and middle shelf domains (Figure 1). Even shearwaters, which do not breed in Alaska and thus were not tied to colonies in summer, clustered near the Alaska Peninsula in summer where krill were abundant, but in fall, they dispersed throughout the shelf and farther north.

There were inter-annual variations in seabird abundance and response to prey distribution, but overall, a key driver of seabird distribution in summer was colony location, whereas in fall, the distribution of forage fish, including capelin and juvenile pollock, was also important.

Why We Did It

Summer and fall can be energetically demanding periods for seabirds. In summer, breeding seabirds need to acquire enough prey close to their breeding colony to feed rapidly growing chicks. Fall is a different type of energy 'bottleneck,' because seabirds need to replenish depleted fat reserves, undergo feather molt and replacement, and prepare for migration. To better understand how seabirds meet these energetic demands, we studied what factors influenced their distribution, and whether they used different areas of the Bering Sea in summer than in fall.

Kathy J. Kuletz. U.S. Fish and Wildlife Service
Robert Suryan, Oregon State University
Sandra Parker-Stetter, University of Washington
Patrick H. Ressler, Alaska Fisheries Science Center
Martin Renner, Tern Again Consulting, Homer, AK
John Horne, University of Washington
Ed Farley, Auke Bay Lab, Alaska Fisheries Science Center
Elizabeth A. Labunski, U.S. Fish and Wildlife Service

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Sandra Parker-Stetter

Euphausiids, or 'krill', are also important prey for many seabird species; these krill were sampled during a Bering Sea Project trawl.

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Understanding Bering Sea Groundfish Populations

USING MODELS TO SHED LIGHT ON PATTERNS AND TRENDS

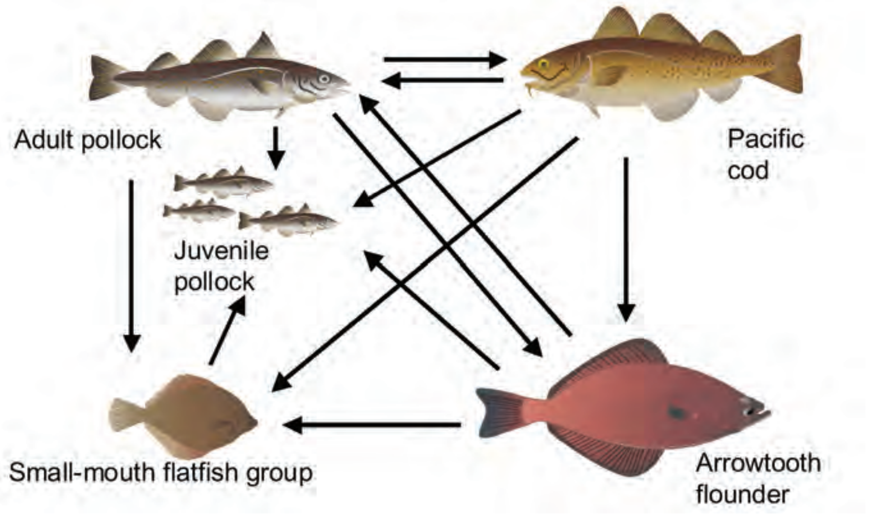
We developed simulation models of predator-prey relationships that allowed us to reproduce observed changes in populations of pollock, cod, and flatfish in the eastern Bering Sea since the 1980s. We learned that, in warm years, age-1 juvenile pollock were more heavily eaten by arrowtooth flounder and cannibalized by adult pollock, whereas fewer age-2 pollock were eaten by cod. These different temperature responses likely reflect different thermal preferences by species, which may change with life stage. For instance, a lingering pool of cold bottom water after cold winters may provide refuge for juveniles, reducing cannibalism by adult pollock. Because of the dominant abundance of pollock, the net effect of warmer temperatures is increased juvenile mortality, resulting in fewer survivors to grow to adults to support future fisheries. We continue to explore ways that environmental conditions alter these relationships, and to evaluate their implications on fishery management and expected future fishery yields.

How We Did It

We developed and evaluated two alternative multispecies fish models for the eastern Bering Sea that consider the interactions among walleye pollock (separated into juvenile and adult groups), Pacific cod, arrowtooth flounder, and a small-mouth flatfish group comprising yellowfin sole, flathead sole, northern rock sole, and Alaska plaice. One type, called a biomass dynamics model, generally performed better than the

continued on page 2

Fig. 1



Predator-prey relationships among eastern Bering Sea fish species included in this study. Arrows represent the directions of predator → prey. Predator-prey relationships were inferred from the contents of fish stomachs sampled during the eastern Bering Sea bottom trawl surveys by the Alaska Fisheries Science Center.

The Big Picture

To understand variability of multiple species in the ocean, scientists often develop whole ecosystem models that attempt to explain the flow of energy from phytoplankton throughout the marine ecosystem. Such ecosystem models tend to be very complicated and require large quantities of data, many assumptions, and large teams of modelers and other researchers. Instead, we developed simpler multispecies models, informed by routinely collected assessment and ecological data, to better understand patterns and trends of the most commercially important fish species in the eastern Bering Sea. Results are intended to foster an improvement in the collective sustainable management of these important fishery resources.

CORRELATIVE BIOMASS DYNAMICS MODEL
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

other type, called a delay difference model. Both models describe the predator-prey interactions among these five groups of fish. Because juvenile pollock serve as prey for all species, juvenile pollock were modeled separately from adults. Our model was developed based on many years of fish stomach samples collected by the National Marine Fisheries Service, Alaska Fisheries Science Center. Once we worked out the predator-prey interactions, we used our models to examine the effects of fishing and environmental factors on these groundfish species based on findings from companion studies.

Why We Did It

Landings of pollock, cod and flatfish account for more than half of all U.S. commercial fishery landings. Annual catch limits are set for each species individually, based on assessments of their abundance and productivity. Yet, patterns in fish abundance are not independent. Good years for pollock and cod reproductive success tend to coincide, and display patterns opposite those for flatfish. Are these trends a result of see-saw patterns in predators and prey, or due to species' responses to environmental variations, or perhaps a result of commercial fishing? Our study intends to develop a deeper understanding of interactions among major groundfish species in the Bering Sea, thereby fostering a joint management approach that acknowledges ecological interactions of these species and the combined effects of climate and fishing.

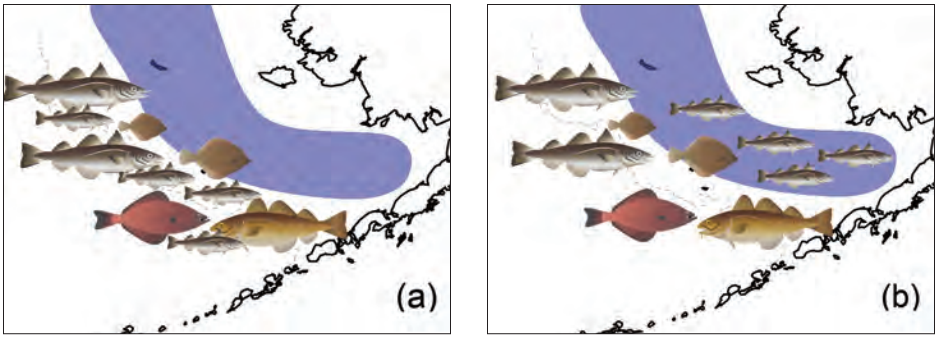
Tadayasu Uchiyama, School of Fisheries and Ocean Sciences, University of Alaska Fairbanks (UAF)

Gordon H. Kruse, School of Fisheries and Ocean Sciences, UAF

Franz J. Mueter, School of Fisheries and Ocean Sciences, UAF

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Fig. 2



Schematic diagrams showing alternative hypotheses on how cold climate may affect distribution of fish on the eastern Bering Sea shelf and predation on young pollock. The cold pool (blue) is a pool of cold water (< 2°C) on the Bering Sea shelf formed by melting sea ice. In cold years, the cold pool covers a large portion of the middle shelf region. Most fish species are driven to the outer shelf region by the cold water, where predation is intensified by increased prey and predator density (a). However, there is some evidence that young pollock (major prey for other fish, including adult pollock) are more tolerant to cold water, in which they are protected from predators (b). If this is the case, predation on young pollock would decline under cold climate and increase under warm climate.

Fig. 3a

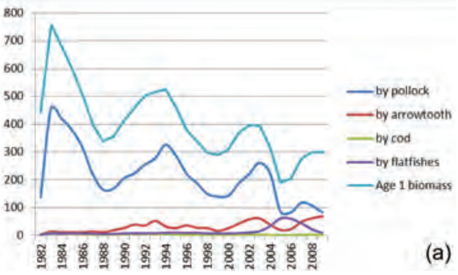
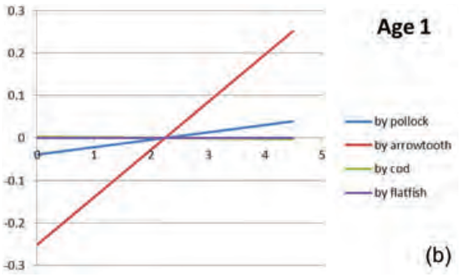


Fig. 3b



(a) Model-estimated biomass of age-1 pollock and age-1 pollock biomass lost to predation by adult pollock, arrowtooth flounder, Pacific cod, and small-mouth flatfishes (values in 1000 metric tons); and (b) Effect of bottom temperature on predation of age-1 juvenile pollock by these same predators. The x axis is bottom temperature in °C, whereas the y axis shows estimated biomass of juvenile pollock lost to predation, expressed as a percentage relative to the biomass lost to predation at the mean bottom temperature of 2.25°C

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

The Contribution of Dissolved Iron from Melting Ice in the Bering Sea

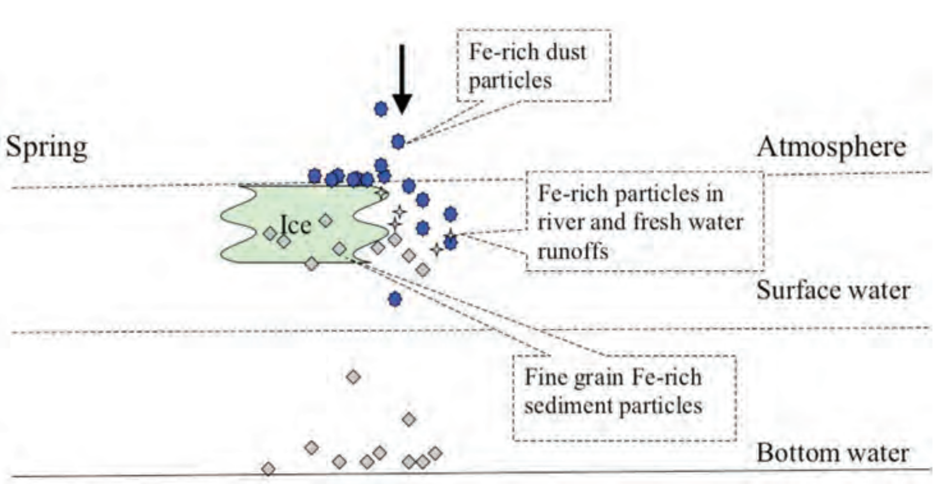
SEA ICE AND IRON – ESSENTIAL SPRINGTIME ROLES

Like humans, algae require the trace metal iron for healthy growth. We tested the hypothesis that although the initial algal growth in spring depletes available iron (Fe) in the winter-mixed surface water of the Bering Sea shelf, resulting in limited algal growth, the input of Fe from melting ice relieves this limitation.

Sea ice can be an important source of available Fe to the surface ocean (Figure 1). Fe-rich particles derived from eolian deposition, fresh water runoff, and sediment suspension can be incorporated into sea ice during its formation. When ice melts in the spring, these Fe-rich mineral particles are released into the water column, and a portion of the particulate Fe becomes dissolved, contributing to the available Fe flux to the stratified surface water. This additional Fe source is especially important to the spring bloom, as vertical mixing of iron-rich subsurface waters is inhibited by the strong water column stratification brought about by the creation of a surface low-density layer of water when the ice melts.

continued on page 2

Fig. 1



Pathways of iron supply from melting sea ice to the water column.


Jennifer Nomura

The Big Picture

We explored the role of sea ice in delivering dissolved iron (DFe), essential to the health of phytoplankton, and found that areas of the Bering Sea outer shelf not influenced by ice contain insufficient DFe for the complete assimilation of available nitrate by algae. In contrast, outer shelf areas influenced by melting sea ice contained sufficient DFe concentrations to support complete biological utilization of nitrate. In addition to providing water column stability, melting sea ice provides a source of DFe to the outer shelf that is important in maintaining ice-edge algal blooms. In the absence of this input, diatom productivity over the outer shelf and shelf break may become limited by iron during spring. Variability in sea ice extent is likely to translate into a varying supply of DFe to the Bering Sea outer shelf and shelf break in early spring, and thereby contribute to changes in the timing and community composition of the spring phytoplankton bloom.

A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

How We Did It

Our dissolved iron (DFe) measurements from both water column samples and ice cores collected during the 2007- Bering Sea Project cruise indicate that the melting ice provided substantial DFe to the water column. This additional DFe input, while highly variable (Figure 2), was particularly important to shelf break surface waters. In the absence of this Fe source, the concentration of DFe in the surface water would not be sufficient to allow algae to utilize fully the high nutrient concentrations observed in the outer shelf, and the productivity of this area would be limited below its full potential. The particulate Fe in the ice cores was 1 – 2 orders of magnitude higher than the DFe in the ice core. If only a portion of this is bioavailable, it represents a further substantial source of Fe from the melting ice.

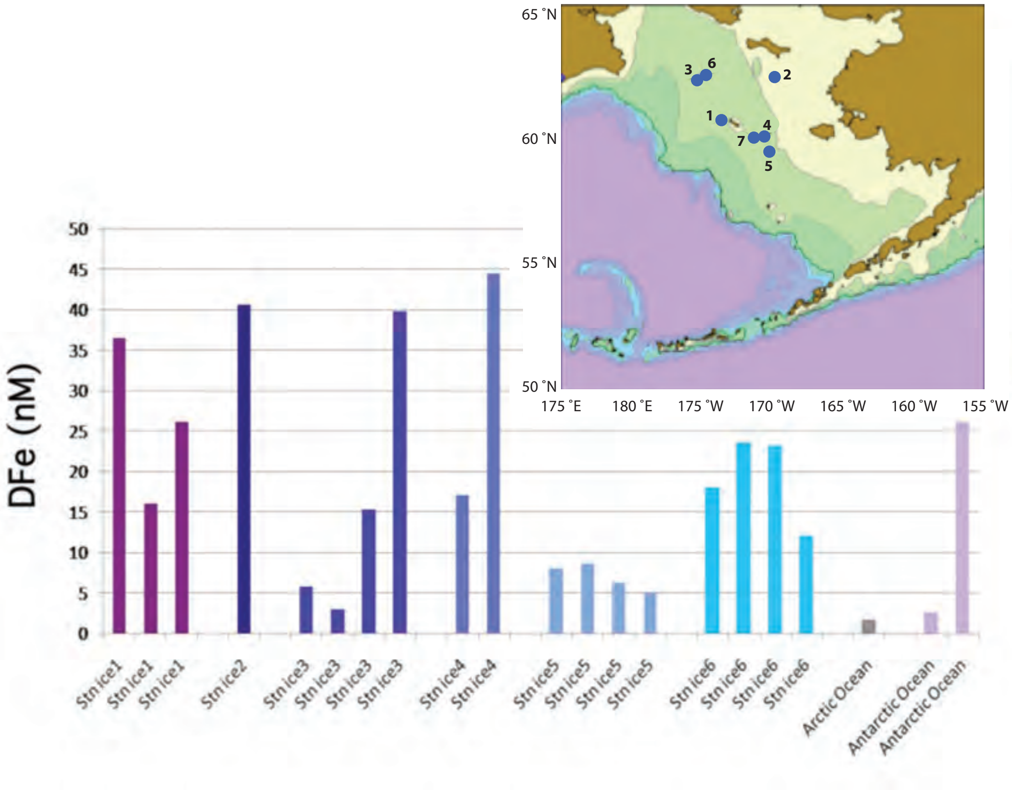
Why We Did It

The Bering Sea is one of the most productive regions in the world. It exhibits a band of exceptionally high productivity along the shelf break during spring and summer. Previous observational and modeling studies indicate that changes in the seasonal ice cover influence open-water productivity (the timing of the spring bloom and the composition of the phytoplankton community) over the Bering Sea shelf and shelf break.

Erika Acuna

The timing of the spring bloom also affects the transfer of energy to upper trophic levels. Because the outer shelf contains much higher concentrations of macronutrients, particularly nitrogen, than the middle and inner shelf, an ice edge that reaches the outer shelf in spring has the potential to support a larger ice edge phytoplankton bloom as ice begins to melt. However, high macronutrient concentrations in the outer shelf can only be fully assimilated when enough iron is available. We determined the acutely important influence of ice melt on the distribution of DFe, compared to available macronutrients in this area, and its possible implications for the spring phytoplankton bloom.

Fig. 2



Dissolved iron concentrations from replicate samples in the sea ice of the Eastern Bering Sea shelf in April/May 2007, with data from the Arctic and Antarctic Oceans for comparison.

Jingfeng Wu, Rosenstiel School of Marine and Atmospheric Science, University of Miami

Ana Aguilar-Islas, Institute of Marine Science, University of Alaska Fairbanks

Rob Rember, International Arctic Research Center, University of Alaska Fairbanks

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Aging Murres in a Warming Sea

OLD AGE AND EXPERIENCE BEAT YOUTH IN POOR CONDITIONS

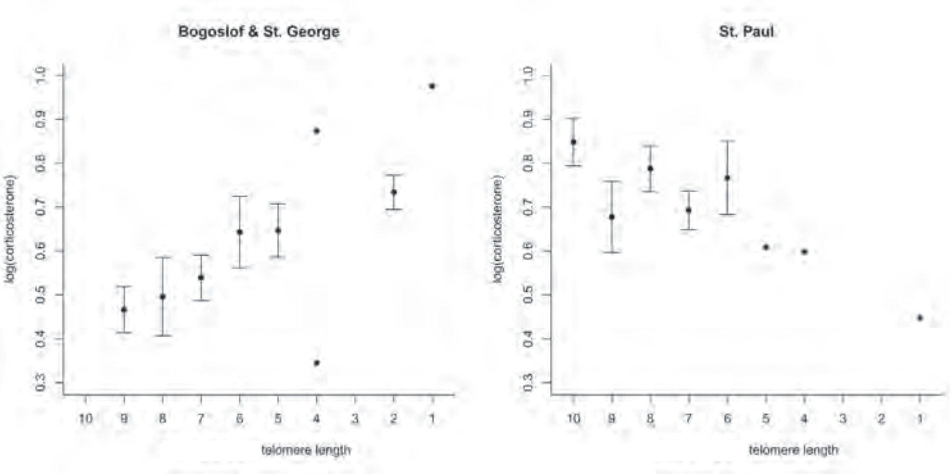
Thick-billed murres (*Uria lomvia)* are a common seabird in the Bering Sea. Better understanding of their demography and life history is crucial to predicting their role as an indicator of a changing ecosystem and how they may respond to worsening conditions or future changes in the dominant climate patterns of the Bering Sea. Our project explored the relationship between biological age and environmental conditions in thick-billed murres with breeding grounds in the Bering Sea. Murres are long-lived animals, and in the wild may survive up to a venerable age of 30 years old, while adapting to dramatic manmade and climate-induced changes in their environments.

How We Did It

We measured telomere length (a DNA marker) as an indicator of biological age, and compared it among three murre colonies in the southeastern Bering Sea that have contrasting environmental conditions and population trajectories. Providing a more accurate picture of an organism's true aging process, biological age is a measure of aging that integrates chronological age

continued on page 2

Fig. 1



Nutritional stress (measured by corticosterone levels) increases with age on high quality colonies (left: Bogoslof and St. George) and decreases on poor quality colonies (St. Paul). Note that since telomere quantity decreases with age, the x-axes run from large quantities to small so as to run from young to old, as a chronological age axis would.


RAM PAPISH

The Big Picture

The Bering Sea system is characterized by ice covered winters and complex interactions of food webs and water masses during the summers. Seabirds are top predators, and they act as land-based indicators of various changing marine signals: fish stocks, timing of annual marine food web changes, and climate-related fluctuations in the environment. Some long-lived seabirds, with lifespans easily reaching 30 years, may have witnessed two or more radical regime shifts in the environment. Our work has demonstrated that longevity is an important factor in how seabird populations respond to their environment: age and environmental conditions interact to explain the stress levels that affect reproduction and survival of breeding murres.

PATCH DYNAMICS STUDY, PRIBILOFS AND NORTH BERING SEA
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

(time since birth) with the effects of stress, reproduction, and individual variability. As organisms age, their physiological deterioration may lessen their ability to meet environmental challenges. On the other hand, older birds may be more experienced and be better at responding to the environment: they know where to forage when conditions have changed.

Our results demonstrate that stress levels of breeding thick-billed murres depend on an interaction of colony conditions and biological age (Figure 1). When conditions are favorable, such as on Bogoslof Island, or relatively stable (e.g., St. George), biologically older birds have higher stress levels, likely due to the effects of aging. When conditions are poor, such as on St. Paul Island, biologically older birds have lower stress levels. We concluded that older birds are more experienced, but also might be less fit in obtaining food than younger individuals. When food is plentiful, prior experience in finding food is less important, but as conditions worsen, the experience of older individuals becomes beneficial. Under the worst conditions, all birds become food limited; here older birds outperform younger ones, as their experience in finding food and weathering tough years becomes more important than their failing physiology.

Why We Did It

Although population modeling estimates demographic parameters, the age structures of wild populations are often unknown. However, knowing the makeup of populations and how different age classes perform in the environment is crucial to our understanding of animals' responses to that environment. Especially in long-lived organisms, like seabirds, adults can vary in their quality and ability, based on biological age. If the environment becomes less predictable, is it better to have populations comprising younger or older birds responding to that situation? Is a colony of old birds in trouble, or will it be more likely to weather poor foraging conditions successfully? Knowing that younger birds are poor foragers or that older birds are more stressed could help explain why some colonies do well and others decline.

Rebecca Young, Institute of Arctic Biology (IAB), Department of Biology and Wildlife, University of Alaska Fairbanks (UAF)
Chris Barger, IAB, Department of Biology and Wildlife, UAF
Ine Dorresteijn, IAB, UAF
Sasha Kitaysky, IAB, Department of Biology and Wildlife, UAF

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Murres breed in dense colonies on sea cliffs in the circumpolar north.

RAM PAPISH

BEST-BSIERP
Bering Sea PROJECT
UNDERSTANDING ECOSYSTEM PROCESSES IN THE BERING SEA 2007–2013

Steps Toward Predicting the Future of the Bering Sea Fish Catch

HOW COMPUTER MODELS HELP FISHERMEN FIND THE "COLD POOL" ... AND DINNER

With the Bering Sea bringing in over 50% of the US fish catch, there are some obvious advantages to fishermen, fish resource managers, and markets if we can predict, even just by some months, which fish stocks will do well. One clue to this is to understand the creation and fate of the eastern Bering Sea "cold pool," a region on the Bering Sea shelf about the size of California below 2°C (~36°F). This "cold pool" (which changes through the year and from year to year) is important for crab and bottom-fish distributions. For example, it acts as a barrier to northward migration of some types of fish, e.g., walleye pollock, one of the largest and most valuable fisheries in the world. Can we predict how this cold pool will change and where it will be found? We found that, using a good computer simulation, to some extent, we can.

How We Did It

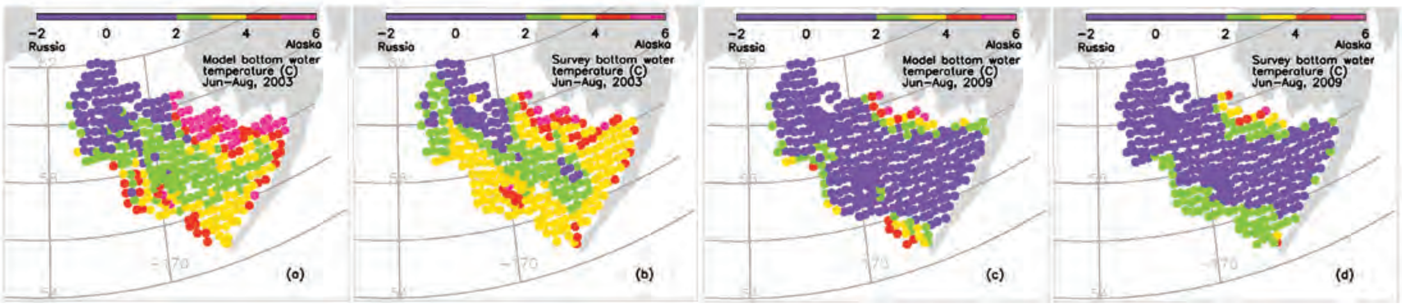
We used a state-of-the-art computer model focused on simulating the ocean and sea ice of the Bering Sea. To enable it to be near real-time, this BESTMAS (Bering Ecosystem STudy ice–ocean Modeling and Assimilation System) model is driven by atmospheric forcings from the weather forecasting models of the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR).

continued on page 2

The Big Picture

Although the Bering Sea is small compared to the world ocean, it is still too big to measure all of it at one time, other than by satellites (which can only measure the surface). Thus, to study the whole system, we created a virtual reality, a computer model of the system from the seafloor to the sea ice surface. This virtual reality is based on our understanding of the physics, chemistry and biology of the real world and (crucially) is tested against measurements we can make. Researchers, managers and fishermen can then use this model as a tool for understanding, as a framework for their measurements, and (given enough model skill) as a predictor of the system and where, for example, to find the cold pool ... and hence dinner.

Fig. 1



Eastern Bering Sea shelf bottom water temperatures (°C) from ship-based surveys (right column) and corresponding BESTMAS model results (left column) for 2003 (a warm year, upper panels) and 2009 (a cold year, lower panels). The cold pool is marked by purple color. This figure shows that BESTMAS is able to capture reasonably well the spatial patterns of observed spring-summer bottom layer temperature fields and the distribution and extent of the cold pool (purple region) for both cold and warm years.

THE IMPACT OF CHANGES IN SEA ICE ON THE PHYSICAL FORCINGS OF THE EASTERN BERING ECOSYSTEM - RETROSPECTIVE INVESTIGATION AND FUTURE PROJECTION
A component of the BEST-BSIERP Bering Sea Project, funded by the National Science Foundation and the North Pacific Research Board with in-kind support from participants.

This model runs on a computer cluster (connected computers that work together) at the University of Washington, where simulating one year of the Bering Sea ice-ocean system takes about four hours of computer time. We found the model's sea ice—one of the drivers of the cold pool formation—matched well with data from satellites. Moreover, we found that the extent and location of the cold pool in the model agreed well with ship data from the region, in the years where ship data was available (Figure 1).

So then we can use the model to study what the cold pool looked like in years when there wasn't ship data, and, most importantly, to consider why and how the cold pool forms, and how the cold pool changes over the season. From this, we found out, for example, that the simulated field of bottom layer temperature on the Bering Sea shelf at the end of May is a good predictor of the distribution and extent of cold bottom waters throughout late spring and summer (Figure 2). Thus, we can use the model results from the end of May to predict what the spring and summer will be like some months in the future.

Why We Did It

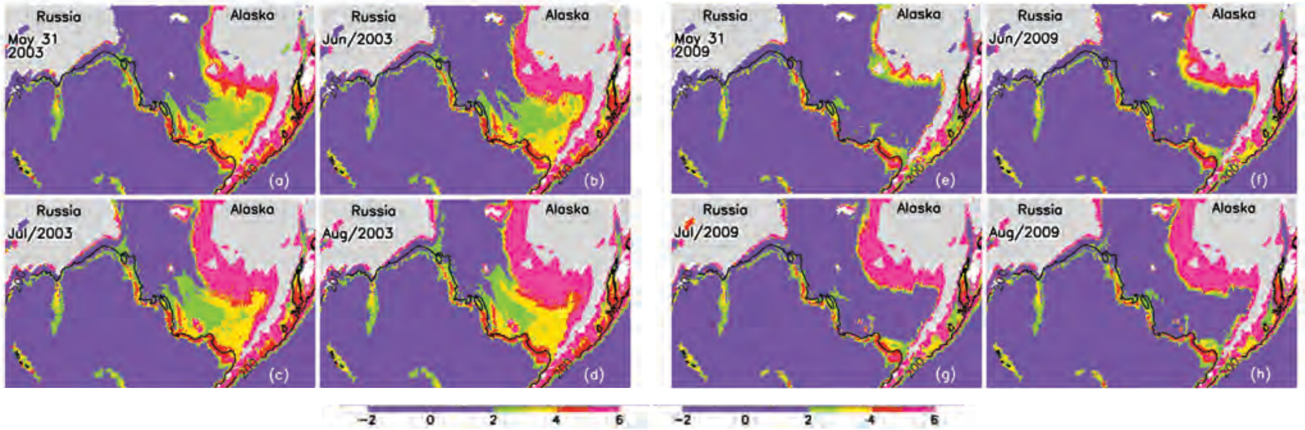
Quantifying the cold pool is a key part of predicting the balance of fisheries in the Bering Sea. The location and duration of the cold pool changes a lot during the year and from year to year, dependent on atmosphere, ocean and sea ice conditions during the previous winter. All these preconditions interact, but a coupled ice-ocean model such as BESTMAS allows us to combine all these effects in a physically consistent manner, and make predictions of the cold pool location and extent months in advance.

Jinlun Zhang, University of Washington
Rebecca Woodgate, University of Washington

The Bering Sea Project is a partnership between the North Pacific Research Board's Bering Sea Integrated Ecosystem Research Program and the National Science Foundation's Bering Ecosystem Study. **www.nprb.org/beringseaproject**

Armchair Oceanography. The University of Washington computer cluster MIZ (Marginal Ice Zone) used to run the BESTMAS model, alongside the creator of the BESTMAS model, Jinlun Zhang.

Fig. 2



Simulated May 31 daily mean and June, July, and August monthly mean fields of bottom water temperature (˚C) for 2003 (a warm year) and 2009 (a cold year). Black line represents the 200 m depth contour. Purple shows areas of bottom temperatures below 2˚C, representing, on the Bering Sea shelf (i.e., between the 200 m contour and Alaska), the cold pool extent. This figure shows that the simulated field of bottom layer temperature on the Bering Sea shelf on May 31 is a good predictor of the distribution and extent of the cold pool throughout late spring and summer, for both cold and warm years.