Implementation Plan

Bering Ecosystem Study Program

(BEST)

BEST Science Steering Committee

September 2005

This material is based on work supported by the National Science Foundation (NSF) under grant # ARC-051826. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

Bering Ecosystem Study Program (BEST) Implementation Plan

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I. Executive Summary

The goal of the Bering Ecosystem Study (BEST) Program is to develop a fundamental understanding of how climate change will affect the marine ecosystems of the eastern Bering Sea, the continued use of its resources, and the economic, social, and cultural sustainability of the people who depend on it.

In recent years it has become increasingly apparent that the ecosystems of the eastern Bering Sea, spanning from the Aleutians to St. Lawrence Island, and from the inner shelf to the slope, are changing concurrently with fluctuations in the climate patterns of the region. These ecosystem changes have important ecological implications for the productivity and the food webs of the Bering Sea, ranging from planktonic organisms to the upper trophic level fish and marine mammals targeted by subsistence and commercial harvests. These ecological changes are also likely to impact the social, economic, and cultural systems of the people dependent on Bering Sea resources. Thus, an understanding of coupled physical-biological-social dynamics is essential for the sustainable management of eastern Bering Sea resources in the face of future ecological, social, economic, and cultural change.

This Implementation Plan outlines the first phase of a ten-year research program focused on the marine ecosystems of the eastern Bering Sea and the people dependent on its resources. To improve understanding of the variables and processes shaping all aspects of the Bering Sea, from physical forcing (atmosphere and ocean) to food web responses including fish, seabirds, marine mammals, and humans, fundamental research in the physical, natural, and social sciences, appropriate for funding by the National Science Foundation (NSF), will be linked to studies funded by other agencies with interests in this important region. The BEST Science Plan (www.arcus.org/Bering/science_plan.html) outlines a broad range of questions important for understanding how climate variability could influence the ecosystems of the eastern Bering Sea and their ability to sustain the goods and services required by people. Social scientists developed a parallel Science Plan, Sustaining the Bering Sea (www.arcus.org/Bering/hbest/index.html), which outlines a community-based research program focused on the residents of Bering Sea communities and their need to understand how climate variability will affect their future. These two initially separate programs have now been integrated into a single program that will study the ecosystem as a whole, including the social implications of climate change and the roles of people in the system.

Because the drafters of the natural and social science Science Plans foresaw the need for a more ambitious science program than the available resources could support, implementation of the BEST program will follow a two-phase approach. Initially (2007–2010), research will focus on a comprehensive investigation of the impacts of seasonal sea ice on the eastern Bering Sea (Section V). This emphasis is motivated by the critical role sea ice dynamics play in structuring the physical marine environment and the food webs of the Bering Sea, by evidence of recent declines in seasonal ice cover, and by the importance of sea ice in subsistence activities. *Understanding the role of changing sea ice conditions (extent, concentration, thickness, and seasonality) on the chemical, physical, and biological characteristics of the ecosystem and human resource uses is the most urgent research priority of the BEST Program. The study of changing sea ice dynamics and its impacts on ecosystem processes and sustainable harvests encompasses many of the individual processes important to the BEST Program.* As additional resources become available, it is expected that BEST will develop a second phase in which other components of the two Science Plans will be developed into research programs (modules 2–5, Appendix 1).

The temporal and spatial scales of the field research will be influenced by the duration of the initial phase of the program (4 years) and by logistical limitations (e.g., ship-time availability). Given the expected duration of the field program, BEST activities will initially focus on interannual variability during spring (March–June) and will target the eastern shelf of the Bering Sea, from the Aleutians north to St. Lawrence Island. Social science research will complement the natural science but is not limited to the March–June time frame or to the exact geographical parameters just noted.

The BEST program will bring together physical, biological, and fisheries oceanographers, ecologists, climatologists, archeologists, anthropologists, economists, and other social scientists in a highly integrated and interdisciplinary program. The work will draw on regional historical datasets derived from modern oceanographic programs over the past several decades, longer-term instrumental and written records, and knowledge of ecological change recorded by the multigenerational observations of local populations. BEST will develop the next generation of conceptual and numerical models needed to link ecological and physical change and provide better strategies to anticipate and ameliorate climate-induced impacts on subsistence and commercial resource users.

The study of ecosystem changes in the eastern Bering Sea will involve the investigation of a full suite of variables and processes that are linked ecologically but divided by the research mandates of different agencies and organizations. The BEST program must therefore be capable of integrating a variety of complementary research efforts to develop a unified understanding. Researchers in BEST will need to develop collaborations with scientists in a number of agencies with different mandates (see Section IV). Collaborations among scientists funded through the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), North Pacific Research Board (NPRB), Bering Sea/Aleutian Salmon International Survey (BASIS), Alaska Ocean Observing System (AOOS), U.S. Geological Survey (USGS), and U.S. Fish and Wildlife Service (USFWS) will be required to accomplish an end-to-end understanding of the eastern Bering Sea ecosystem and its users. In the face of the rapid ecosystem changes underway, this understanding is essential to sustain the rich marine resources of the eastern Bering Sea and the people and cultures dependent on their harvest.

II. Background and Rationale

Planning for a comprehensive study of the eastern Bering Sea began in September 2002 with a planning workshop in Laguna Beach, California. Workshop participants agreed unanimously that there was an urgent need to improve understanding of the linkages between climate variability and the responses of the ecosystems of the Bering Sea, as detailed in the workshop report (http://www.arcus.org/Bering/Downloads/LagunaBeach.pdf). Participants agreed that the emphasis should be on the eastern Bering Sea, in particular the continental shelf and shelf-slope region where the commercial and subsistence activities by the United States are concentrated (Figure 1). This is also an area where earlier research programs, such as the Outer Continental Shelf Environmental Assessment Program (OCSEAP; 1974–1992) and the Processes and Resources of the Bering Shelf (PROBES; 1974–1982), provide a strong basis for developing comparative studies.

In March 2003, a second planning workshop convened in Seattle, Washington, to develop a science plan for the Bering Ecosystem Study (BEST) Program (http://www.arcus.org/Bering/index.html). The BEST science plan outlines a multi-year research effort that will provide an improved understanding of the effects of climate variability, at various temporal and spatial scales, on the ecosystems of the eastern Bering Sea (http://www.arcus.org/Bering/science_plan.html). The proposed studies focus on mechanisms and processes that determine the biological productivity of the Bering Sea ecosystems and the fate of this production as it is transferred through the ecosystem from primary producers to upper trophic level consumers, including humans. Thus, the BEST

Program acknowledges, *a priori*, the need to understand the role of upper trophic level consumers, including marine mammals and people, as agents that structure the marine ecosystems on which they depend. In March 2004, a workshop was convened in Anchorage, Alaska, with Bering Sea residents and social scientists to outline possible goals of a social science plan for the Bering Sea. This workshop led to the development of the social science component of BEST, entitled *Sustaining the Bering Sea Ecosystem: A Social Science Research Plan* (http://www.arcus.org/Bering/hbest/index.html), which has been integrated into this implementation plan.

Appointed in March 2005, the BEST Science Steering Committee (SSC; Appendix 3) was tasked with developing plans for prioritizing the research questions outlined in the BEST science plan and for implementing a field program starting in March 2007 as part of the International Polar Year 2007–2008 (IPY). Between March and April 2005, the BEST SSC met by teleconference and developed a draft implementation plan that was posted on the web and e-mailed to individuals who had expressed an interest in BEST. In May 2005, an open implementation workshop to review the draft implementation plan was held in Victoria, British Columbia, on the first day of the GLOBEC Symposium on Climate Variability and Sub-arctic Marine Ecosystems. Over 130 participants attended the workshop and provided suggestions for revisions.

The Bering Ecosystem Study (BEST) program presents an ambitious vision for the integration of ecological research from physical oceanography to social science—with an explicit effort to link scientific discovery to an understanding of the challenges that residents and users of the eastern Bering Sea may face under continued climate warming and loss of sea ice. To this end, BEST will engage the tools of physical and biological oceanography, social science, and quantitative modeling to develop a better understanding of the *end-to-end* ecodynamics of the eastern Bering Sea. BEST will seek to partner across multiple federal and state agencies, Native and other communities of users, and international research programs.

The eastern Bering Sea (Figure 1) supports productive marine ecosystems and extraordinarily rich marine resources. These resources include vast numbers of marine birds and mammals—among which are federally protected species—and productive commercial stocks that generate more than 50% of all fish and shellfish landings in the United States.

These fisheries employ local and itinerant fishers, processors, and distributors within and outside of the region. The Bering Sea is also directly or indirectly the source of over 25 million pounds of subsistence foods used by nearly 55,000 local residents, primarily Alaska Natives in small rural communities. Yet major recent ecological changes and future climate change scenarios indicate large impacts on the marine food webs and local human communities in the

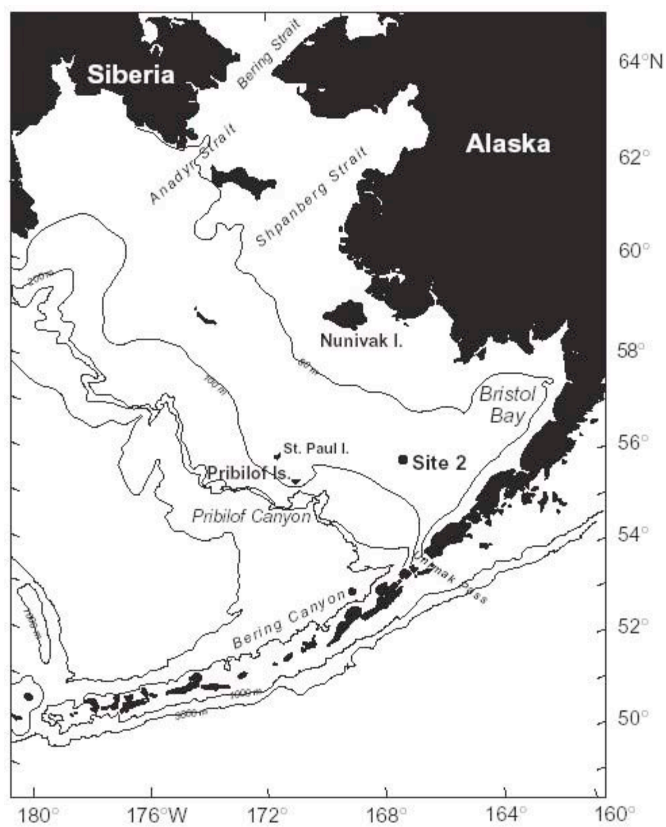

Figure 1. *The Eastern Bering Sea, showing the major bathymetric features, passes and straits, and the location of 50 m, 100 m, 200 m, 1000 m and 3000 m depth contours. Site 2 indicates the location of NOAA's mooring M-2. Figure courtesy of P. Stabeno (NOAA).*

region. As the Bering Sea responds to variations in climate, its ability to support the resources on which people depend may change. **The goal of the Bering Ecosystem Study (BEST) Program is to develop a fundamental understanding of how climate change will affect the marine ecosystems of the eastern Bering Sea, the continued use of its resources, and the economic, social, and cultural sustainability of the people who depend on it.**

Recent changes in the marine ecosystems of the eastern Bering Sea have, in many cases, been correlated with physical variability. For example, the eastern Bering Sea is in transition from a system dominated by cold water and arctic taxa to a temperate system in which sub-arctic species may come to dominate; the rate of change appears to be accelerating. Population explosions of jellyfish have come and gone, episodic die-offs of breeding and migrant seabirds have occurred, there have been sharp declines in fur seal and sea lion populations, as well as in some salmon runs in western Alaska rivers. As this transition evolves, an understanding of the underlying processes responsible for these ecosystem responses will provide the basis for good future stewardship and a way to mitigate negative impacts on people who depend on the biological resources of the region.

Two major external physical forcing mechanisms dominate long-term changes in the eastern Bering Sea dynamics: atmospheric forcing (via winds and shortwave, longwave, latent and sensible surface heat fluxes) and water transport through the Aleutian Passes and Bering Strait. Variability in these forcing mechanisms occurs on multiple spatial and temporal scales, including local episodic events (storms), interannual variability at the scale of the eastern Bering Sea, and decadal and longer-term climatic events operating at North Pacific- and global-scales. Issues of particular importance include the effects of this external forcing on the dynamics (timing, extent, thickness, and spatial distribution) of sea ice, the re-supply of nutrients to the eastern continental shelf, alterations of summer heating and stratification, changes in mesoscale eddy properties and statistics, shifts in tidal mixing, currents, and flow through the Bering Strait and Aleutian Island passes.

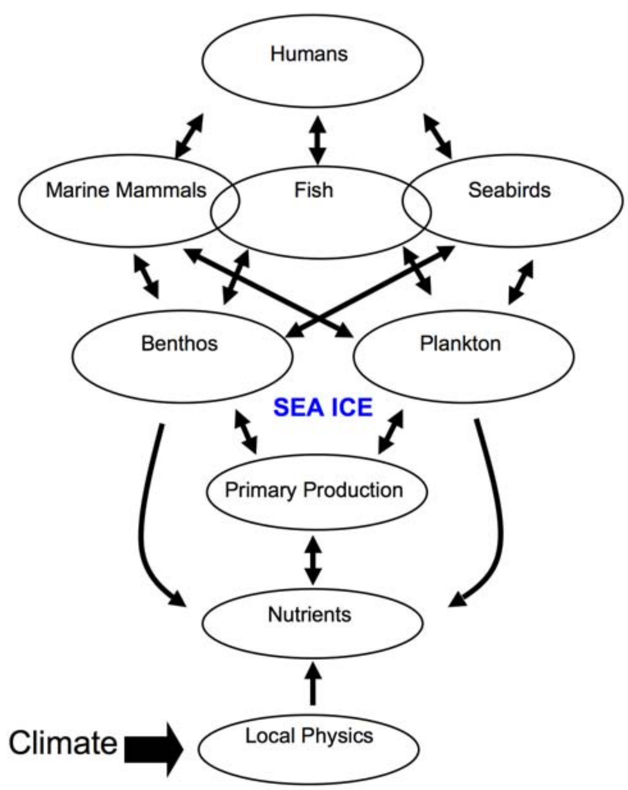

__Figure 2.__ Cartoon of Bering Sea food webs showing the hypothesized role of sea ice as a determinant of the fate of primary production.

Physical features of the marine environment that influence the responses of the Bering Sea biota to this external forcing include: 1) sea ice, which affects underwater light fields, water column temperature structure, spatial extent of the summer cold pool, and the availability of physical substrate for ice algae and other ice-associated organisms, such as walrus and ice seals which need ice for hauling out; 2) stratification of the water column, which affects the availability of light and nutrients needed to support primary production, as well as the vertical distribution of many of the smaller planktonic organisms; and 3) water temperature, which affects the rates of physiological processes, as well as the vertical and horizontal distribution and aggregation of fish.

Seasonal sea ice cover is a dominant feature of the eastern Bering Sea and a pivotal factor for structuring the physical environment and ecosystems on the shelf (Figure 2). The timing of sea ice retreat affects the onset and possibly the fate of the spring phytoplankton bloom. The broader ecosystem consequences of changes in the timing of the bloom, however, need to be determined. There is evidence that water temperature during the spring phytoplankton bloom affects the productivity of copepods and possibly the recruitment of important commercial fish species, such as walleye pollock (*Theragra chalcogramma*). Moreover, decadal-scale shifts in climate have the potential to shift the control of pollock populations between top-down and bottom-up, with important implications for marine predators (fur seals, birds), human subsistence and commercial harvests, and fisheries management. These hypotheses have not been empirically tested.

Pools of cold (< 2°C) bottom water in the summer are a signature result of sea ice formation or melt on the eastern Bering Sea shelf, but the effects of changes in the size, duration, and distribution of these cold pools on the circulation and the ecology of the shelf remain open questions. The potential consequences of a future loss of these cold pools to the productivity and food webs of the eastern Bering Sea are not known. If the hypothesized warming of the bottom water allows the northward range expansion of epibenthically-feeding fish, competitive pressures could impact benthic-foraging marine mammal populations.

These unanswered questions highlight the need for the development of quantitative and predictive tools to integrate the effects of climate change across spatial and temporal scales and to forecast how marine ecosystems might behave under different climate scenarios. Existing models currently address regional circulation patterns and climate variability in the North Pacific and the Bering Sea. There are presently no models, however, that link global climate forcing, through physical oceanography, through the impact on functional biotic groups and communities, and up to the broader ecosystem consequences of these responses, including potential impacts on the local communities and commercial fishers harvesting Bering Sea resources for their livelihoods.

Alaska Natives, for example, fear for the future of their cultural systems in the face of the anticipated large-scale environmental changes predicted by global climate models. The loss of sea ice may bring about dramatic changes, including the loss of hunting opportunities, declining food security, health problems, potential increases in marine traffic, pollution, and increased economic and industrial development. Likewise, commercial fishing opportunities are likely to shift spatially and temporally, as some species cease to be commercially important and others expand in importance. The warming of the Bering Sea may impact people in other unprecedented ways, including the development of harmful algal blooms (HABs) that could impact the food webs supporting commercial and subsistence harvests. Anthropogenic sources of contaminants may also increase in a warmer system (e.g., introduction of new compounds and changes in their distribution and abundance) due to changes in anthropogenic sources (e.g., opening of new shipping lanes) and physical vectors (e.g., ocean circulation and atmospheric patterns).

Better anticipation of such effects can be accomplished through an *end-to-end* approach that seeks to understand the ecological implications of climatic forcing on food webs and that includes humans as components of an integrated system (Box 1).

BOX 1. Integrating multiple dimensions in an *end-to-end* program

BEST presents an ambitious *end-to-end* vision for the integration of interdisciplinary research—from physical oceanography to social science—with an explicit effort to direct scientific discovery towards research that addresses how continued climatic warming and loss of sea ice in the eastern Bering Sea will affect the resident communities and non-resident resource users who depend on the region.

An increased understanding of the ways Bering Sea ecosystems are intertwined in the social, economic, and cultural life of the local residents and seasonal users is fundamental to link the physical and ecological impacts of climate change with the people who depend on these ecosystems. This integrated *end-to-end* perspective, stretching from climate forcing to social consequences, is also of benefit to the people who live and work in this region.

Many residents and non-resident resource users from the Bering Sea have contributed to the development of the BEST Implementation Plan. Residents of Aleut, Yupik, and Inupiat villages around the eastern Bering Sea provided opinions on the research that they felt would be most useful. Commercial fishers also provided input on their specific needs for information on Bering Sea ecosystems. Some of the questions raised by resident and non-resident resource users are echoed in this BEST Implementation Plan.

The parallels between the interests of the science community and those of Bering Sea stakeholders suggest that the BEST program has considerable potential for addressing pressing social and economic concerns. Additionally, local communities and resource users are effectively positioned to collaborate with scientists by sharing their unique perspectives on the changing Bering Sea environment. Scientists are likewise in an unprecedented position to establish partnerships to collect and share relevant data with the communities of users and residents in the Bering Sea. Thus, an integral part of BEST will entail designing an effective outreach program to forge effective partnerships with local communities and resource users, and to disseminate research results to these stakeholders in ways that will allow them to plan more effectively for the anticipated environmental changes.

Because climate research has relevance for a broad constituency of Native communities, fishers, resource managers, and policy makers throughout the Arctic and the North Pacific Ocean, it is imperative that the BEST program addresses the human dimensions of physical and ecological change in the eastern Bering Sea. There is a critical need to understand how subsistence, social structure, economic inter-dependence, public health, and political access have been, and could be, affected by changes in the productivity, timing, and geographical distribution of culturally and economically important resources. To ensure the success of this *end-to-end* approach, BEST research activities will include vigorous outreach and education components designed to involve a broad array of stakeholder communities.

III. Objectives

The BEST Program will address four major areas of inquiry:

1. **What mechanisms control the linkages between global and regional climate processes and the physical oceanography of the eastern Bering Sea?**
2. **How does variability in the physical aspects of the marine system affect ecosystem processes and structure?**
3. **How will changes in ecosystem productivity and structure affect the sustainability of the marine ecosystems of the eastern Bering Sea?**
4. **In what ways are the social and economic systems that rely on the resources of the eastern Bering Sea vulnerable to physical and ecological changes in marine ecosystems?**

To answer these questions, BEST will focus on a series of research modules that address specific climate-driven changes in the marine environment of the eastern Bering Sea, supplemented by regional studies that will elucidate relevant key processes in selected geographic areas. The questions that drive these research modules include:

Seasonal sea ice cover and ecosystem response. How will the physical characteristics of sea ice vary under scenarios of climate change? How will changes in sea ice affect the timing, species composition, intensity, and fate of sea ice algae and phytoplankton blooms (Figure 2)? How will changes in the pathways or efficiencies of transfer of energy to the upper trophic levels influence the species composition, biomass, and distribution of zooplankton, fish, marine mammals, and seabirds, and their availability to people? How will changing sea ice affect human mobility and access to subsistence and commercial resources?

Water temperature and ecosystem response. How will temperature changes in the upper mixed layer influence the species composition, competitive interactions, and trophic dynamics in pelagic and benthic ecosystems? What implications do changes in species distributions and rates of recruitment and juvenile survival have for the populations of adult fish targeted by marine predators and human fishers? How will temperature changes in near-bottom waters influence the distribution and interactions of fish and other bottom-tending organisms? How will these distributional changes of motile predators (fish, crabs, whales, walrus, ice seals) affect the abundance and the community structure of their benthic prey? How will the other upper trophic predators exploited by humans (walrus, seals, seabirds) respond to changing sea ice conditions and ecosystem structure?

Ice and atmospheric impacts on nutrient replenishment over the shelf. How will changes in sea ice and atmospheric forcing affect the advection and mixing processes in the eastern Bering Sea that ultimately influence the distribution and abundance of nutrients? What is the relative importance of on-shelf fluxes and *in situ* remineralization in the water column and in the sediments? Can a comprehensive model of the input, internal processing, and output of nutrients on the eastern shelf be formulated and tested with field data?

Social, economic, and demographic response. How have people responded to change in the distribution of sea ice in the past? How are people responding to change now? What economic, social, demographic and cultural variables and structures influence the ability of communities to adapt to changing sea ice characteristics (e.g., distribution, duration, and thickness; Box 2) and in the availability and predictability of subsistence and/or commercial species? How do economic and management structures and programs intersect the social and cultural values held by different communities of Bering Sea residents and users? What dynamics control population changes in permanent and seasonal residents and users of the Bering Sea? How does resource management at federal and state levels affect resident and non-resident users, and how might different management structures affect community vulnerability and adaptability under environmental change?

Box 2. Social implications of changing eastern Bering Sea ecosystems

Aspects of climate and ecological change of interest to Bering Sea residents and resource users:

- Ecosystem health
- Spatial predictability of fishery resources
- Trends in subsistence and commercial resource populations
- Onset and duration of oceanographic regimes
- Loss of sea ice
- Effects on modes of transportation and hazards of travel
- Availability of subsistence foods
- Availability of traditional and culturally important resources
- Changing economic opportunities; economic vulnerability
- Impacts of development on the environment and communities
- Environmental contaminationand food safety
- Public health
- Social vulnerabilities and resilience (adaptability)
- Education and communication about available and emerging knowledge
- Resource management
- Emigration and immigration
- Preservation of language and cultural knowledge

Questions posed by local residents and resource users about Bering Sea ecosystems:

- Are communities going to survive?
- Why is the Bering Sea important to us?
- How did we get to where we are today?
- What factors will influence the future?
- What future do we want?
- How can we get there?

IV. Coordination and Integration

Coordination and integration within BEST and between BEST and relevant research programs and funding agencies will be critical to the development of an *end-to-end* understanding of how climate change will affect the marine ecosystems of the Bering Sea. Internal and external coordination will be required from the beginning of the program to facilitate the effective use of limited resources and to ensure the collection of measurements that are compatible among BEST field and modeling activities, as well as with historical datasets and other pertinent programs.

At least three levels of BEST integration are required: (1) among projects within BEST, (2) between BEST and other relevant eastern Bering Sea programs, and (3) with large-scale North Pacific and international programs concerned with the region. Integration will be especially important to ensure a sound linkage between BEST-generated results on physical oceanography and lower trophic levels and the responses of the upper trophic levels. Upper trophic level responses will, in turn, provide an important link between natural science and social science projects within BEST. Mathematical and simulation modeling will serve as a major quantitative tool for integration within BEST and between BEST and other programs.

Investigators are encouraged to consider three critical areas of coordination and integration when designing their research and outreach activities:

1. **Integration of physical, natural, and social science dimensions within BEST**

The study of the effects of climate variability on Bering Sea ecosystems and their ability to support subsistence and commercial harvests and communities of users will require the integration of scientific information from the physical, biological, and social dimensions of the program. Developing an integrated program, stretching from climate forcing to social systems, is key to providing the information necessary to facilitate the wise long-term management and stewardship of this important marine ecosystem.

This *end-to-end* approach will cover domains ranging from large-scale physics to primary and secondary producers (phytoplankton, zooplankton, larval fish), to upper-trophic predators (forage fish, marine mammals, seabirds, humans), and will require collaborations that link field data collection, retrospective studies, and modeling of various kinds (Figure 3).

To achieve this coordinated *end-to-end* vision, BEST is developing partnerships with other agencies studying specific parts of the Bering Sea ecosystem outside the funding mandate of NSF. For instance, several agencies can contribute valuable physical and biological datasets for this region (Box 3). An ongoing NOAA mooring program will provide time-series observations of physical and biochemical variables relevant to BEST. NASA and NOAA are expected to obtain the satellite remote sensing observations needed to establish a large-scale spatial context for the ship and mooring measurements.

Because studies of upper trophic level species are the responsibility of several different agencies, coordination and integration within and across this trophic level will be particularly critical. The study of large fish will rely on research activities supported by the National Marine Fisheries Service (NMFS), the North Pacific Anadromous Fish Commission (NPAFC), the North Pacific Research Board (NPRB), the U.S. Geological Survey (USGS), and possibly others. The links between zooplankton and forage fish and their predators, including commercially important fish and valuable subsistence species, will connect BEST research with the interests of resource managers seeking to develop ecosystem models and management plans for fishery populations.

Investigations of marine birds and mammals as indicators of ecosystem function will be carried out not only by BEST, but also by the National Marine Mammal Laboratory (NMML) and the U.S. Fish and Wildlife Service (FWS). In particular, ongoing at-sea surveys, tracking studies, and colony-based research on the diets, demography, and foraging effort of these upper trophic predators will help interpret year-to-year fluctuations in a longer term context. Additional efforts to relate the at-sea distributions and abundances of these species

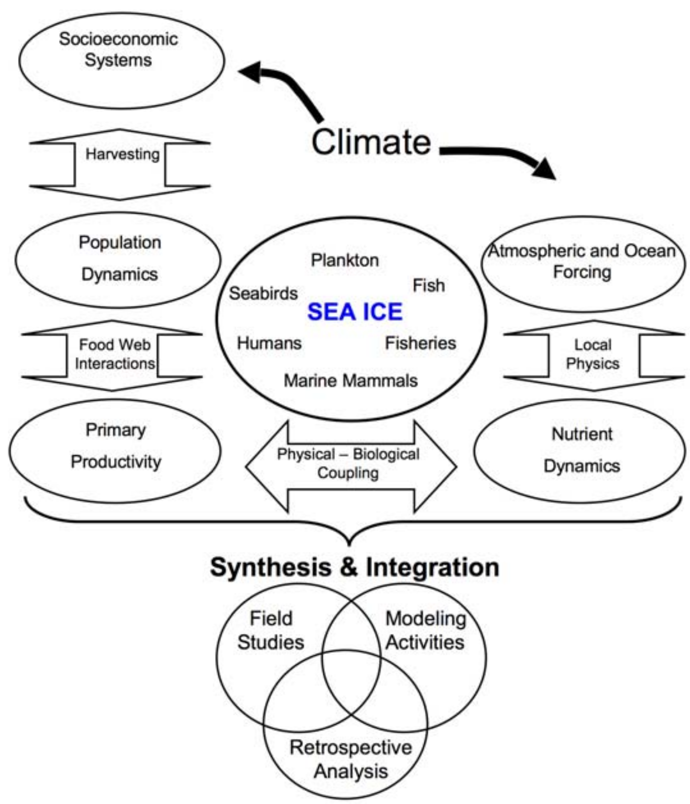

Figure 3. *Diagram of the BEST end-to-end approach and integrated activities to study the eastern Bering Sea marine ecosystems, food webs, and social systems.*

Box 3. Agencies and NGOs with Research Interests Relevant to BEST

- Fish and marine mammal stock assessments: NOAA
- Mammal surveys and rookery-based studies: NOAA and FWS
- Seabird surveys and colony-based studies: FWS
- Remote sensing: NASA and NOAA (NESDIS) and AOOS
- Bio-physical moorings: NOAA and AOOS
- Modeling: potential support from NPRB
- Retrospective analyses: potential support from NPRB

with oceanographic features vulnerable to climate change may also help evaluate the broader ecosystem level roles of these upper trophic predators.

NOAA, the U.S. Fish and Wildlife Service (FWS), and the Alaska Department of Fish and Game (ADFG) are concerned with aspects of human responses to climate change. NSF-funded BEST investigators can collaborate with these agencies through data mining and modeling on upper trophic data sets to investigate the ecosystem effects of "bottom-up" forcing from the lower trophic levels to people. This approach reflects the growing interest in model coupling and integration through natural and social systems (e.g., NSF's Biocomplexity in the Environment Initiative). An improved understanding of human roles in Bering Sea ecosystems, especially as commercial and subsistence users and migrants, will connect BEST research with resource management plans for upper trophic populations, including federally protected species.

BEST will not only seek to develop an understanding of the social science implications of ecological change, but will also work to establish connections between scientists and the human communities of the Bering Sea. This explicit emphasis on addressing the interests and concerns of local inhabitants and non-resident resource users provides a mechanism for wider communication among BEST scientists and the people who live and work in the region.

Annual BEST workshops and coordinated publications will facilitate collaboration and integration of results. Annual workshops involving all investigators should be conducted to ensure effective internal communication and effective collaboration between BEST and other programs. In addition to the principal investigators, the involvement of other project personnel (e.g., post-doctoral and graduate students) and key personnel from cooperating agencies and programs should be encouraged to attend these workshops. BEST workshops may be leveraged by coupling them with other annual conferences, such as the Alaska Marine Science Symposium. The publication of one or more special issues devoted to BEST and related projects in peer-reviewed journals will also facilitate the integration of research, synthesis, outreach, and educational activities.

2. Coordination with other research activities in the eastern Bering Sea

The NSF-funded BEST Program will be closely coordinated and integrated with the new NOAA Fisheries North Pacific Climate Regimes and Ecosystem Productivity (NPCREP) program. NPCREP will be making physical and biological oceanographic observations in support of ecosystem and fisheries oceanography investigations in the eastern Bering Sea during the same time frame as that anticipated for the BEST field program. Together, these integrated field activities will cover the physical-chemical-biological linkages of the eastern Bering Sea ecosystem, from physical forcing (e.g., wind, solar heating) through nutrients, primary production, zooplankton, and fish larvae to upper trophic levels, including humans.

In addition, BEST is partnering with a consortium of agencies and institutions concerned about the Bering Sea ecosystem. Partners in the Climate Change and Bering Sea Ecosystem consortium include: BEST, NOAA (Alaska Fisheries Science Center [AFSC] and Pacific Marine Environmental Laboratory [PMEL]), the North Pacific Research Board (NPRB), the Alaska Ocean Observing System (AOOS), the U.S. Fish & Wildlife Service (FWS), the U.S. Geological Survey (USGS), the U.S.

Arctic Research Commission (USARC), and the University of Alaska Fairbanks (UAF). Individually, members of the consortium investigate particular aspects of the Bering Sea; collectively they will cover most of the abiotic and biotic components of the ecosystem. Members of the consortium met in July 2005 to identify important gaps in their research coverage and to devise a strategy to use their collective resources effectively.

BEST will also establish research and outreach collaborations with the residents of local coastal communities and with commercial fishers. Research among subsistence and commercial hunting and fishing communities will provide data to improve the understanding of human use of Bering Sea ecosystems, and the potential economic and social implications of ecological change.

A non-exhaustive list of potential collaborating organizations includes:

- North Pacific Research Board (NPRB). The mission of the NPRB is to develop a comprehensive science program of the highest caliber to enhance understanding of the North Pacific, Bering Sea, and Arctic Ocean ecosystems and fisheries. Its new science plan emphasizes the development of integrated ecosystem research programs in regions such as the southeastern Bering Sea. http://www.nprb.org/
- Alaska Ocean Observing System (AOOS): A regional component of the developing National Oceanographic Partnership Program, AOOS plans to support moorings and other observing systems in the eastern Bering Sea, as part of a long-term monitoring effort in Alaskan waters. Additionally, monitoring of the high Arctic and Gulf of Alaska AOOS domains may provide a valuable broader-scale perspective for regional comparisons. http://www.aoos.org/
- National Marine Mammal Laboratory (NMML): Marine mammal field studies including vessel-based surveys (e.g., right whales), acoustic monitoring (e.g., blue and humpback whales), and rookery-based telemetry studies (e.g., fur seals, sea lions). http://nmml.afsc.noaa.gov/
- National Marine Fisheries Service (NMFS), Alaska Fisheries Science Center (AFSC): The center is responsible for fisheries oceanographic studies in the eastern Bering Sea and for surveys of the distribution and abundance of fish there. http://www.afsc.noaa.gov/
- North Pacific Fisheries Management Council (NPFMC): The council is responsible for stock assessments and setting fisheries quotas. http://www.fakr.noaa.gov/npfmc/

3. Coordination with research programs in the region

As a U.S. research program, BEST is necessarily focused on the eastern Bering Sea ecosystem. To improve our knowledge of the region as a whole, BEST will seek collaborations with other North Pacific and international programs and initiatives engaged in relevant research and outreach and funding activities. A non-exhaustive list of potential collaborations and opportunities includes:

- The Bering Sea Aleutian Salmon International Survey (BASIS): This collaborative study among the U.S., Japan, and the Russian Federation is funded by the North Pacific Anadromous Fish Commission. Annual late summer and early fall fieldwork by this program provides insight into seasonal cycles in the epipelagic environment (physics, chemistry, plankton, juvenile salmon). http://www.npafc.org/BASIS/
- The BERing & PACific Russia/U.S. Cooperative Research Program (BERPAC): A joint research effort to examine the status of marine ecosystems of the Pacific Ocean and Bering and Chukchi Seas and to assess their role in determining global climate. The objective of BERPAC is to study the biogeochemical cycles of contaminants, related oceanographic processes, and food-web interactions in the North Pacific waters that flow through the Bering and Chukchi Seas, including the study of the behavior of organic pollutants at the water-sediment interface.
- The Arctic Environmental Observatory in Bering Strait: An NSF-funded cooperative research project includes studies of marine mammals and benthic communities on the shallow Bering and Chukchi shelves, community outreach activities at Little Diomede Island, the development

of a seawater environmental system at Diomede Village, and community outreach activities at Little Diomede Island. http://arctic.bio.utk.edu/AEO/

- The International Polar Year (IPY): A major international science initiative involving an intense period (March 2007–March 2009) of interdisciplinary research and data collection, designed to provide a snapshot in time of the state of the polar regions. BEST activities will contribute to IPY objectives. www.ipy.org
- Western Arctic Shelf-Basin Interactions (SBI): Funded through the NSF Arctic System Science (ARCSS) Program and the Office of Naval Research, this project investigates the production, transformation, and fate of carbon at the shelf-slope interface in the Chukchi and Beaufort seas. The field program is complete, and investigators are synthesizing data toward modeling potential impacts of change on the physical and biological linkages between these shelves and adjacent basins. http://sbi.utk.edu/
- Census of Marine Life (CoML): Through cooperation with various CoML field projects (e.g., the Arctic Ocean Diversity project) and data repositories (e.g., Ocean Biodiversity Information System), BEST will have access to historical datasets and contemporary survey data. http://www.coml.org/
- International Whaling Commission (IWC): This international body holds datasets of historical cetacean catches which may be relevant for the retrospective modeling of Bering Sea ecosystems. http://www.iwcoffice.org/
- T/S Oshoro Maru Surveys: Japan, which has been very active in Bering Sea ecosystem research in the past, conducts annual surveys of the eastern Bering Sea shelf. These surveys, which comprise the longest time series of shelf water properties and plankton, are invaluable for examining low frequency variability related to climate since the mid 1950s. http://www.fish.hokudai.ac.jp/wwwfish-e/fac/ship/oshoro/oshoro-e.html
- Ecosystem Studies of Sub-Arctic Seas (ESSAS): Integration with this new regional GLOBEC program, which addresses the effects of changing climate on sub-arctic seas including the Bering Sea, will facilitate regional comparisons. BEST is the U.S. component of ESSAS. http://www.pml.ac.uk/globec/structure/regional/essas/essas.htm
- CLImate VARiability and Predictability (CLIVAR): An international research program that has addressed issues relating to natural climate variability and anthropogenic climate change since 1995. CLIVAR activities include observing and modeling climate changes and decadal variations of the North Pacific, which provides the essential large-scale ocean-ice-atmosphere context for the local processes studied in BEST. As part of the wider World Climate Research Programme (WCRP), CLIVAR is studying the global climate system in partnership with the International Geosphere Biosphere Programme (IGBP) and the International Human Dimensions Programme (IHDP). http://www.clivar.org/
- North Pacific Marine Science Organization (PICES): Established in 1992, PICES is an intergovernmental scientific organization (current members: Canada, People's Republic of China, Japan, Republic of Korea, Russian Federation, and the United States of America). Its goals are to promote and coordinate marine research in the northern North Pacific and adjacent seas especially northward of 30°N; advance scientific knowledge about the ocean environment, global weather and climate change, living resources and their ecosystems, and the impacts of human activities; and promote the collection and exchange of scientific information on these issues. http://www.pices.int/

V. Research Strategy and Priorities

The BEST science plans collectively discuss a broad range of research topics related to climatic, physical, ecological, and social elements of the Bering Sea, and provide important background information in support of this implementation plan. The BEST Scientific Steering Committee (SSC) prioritized and grouped these research objectives into five modules, informed by the questions outlined in the *Objectives* section of this document. Implementation of the BEST program will follow a two-tiered approach. Initially (2007–2010), research will focus on the questions outlined in Module 1. Module 1 outlines on a comprehensive investigation of the impacts of seasonal sea ice on the eastern Bering Sea. This emphasis is motivated by the critical role sea ice dynamics play in structuring the physical marine environment and the food webs of the Bering Sea, and by evidence of recent declines in seasonal ice cover. Module 1 contains the core questions that will receive first consideration for funding. Subsequently, additional modules will be implemented; see Appendix 1 for details on additional modules.

Module 1: What is the impact of the ongoing decrease in seasonal sea ice cover on eastern Bering Sea ecosystems?

1. Synopsis of Module 1 scientific issues

Understanding the role of changing sea-ice conditions (extent, concentration, thickness, and seasonality) on the chemical, physical, and biological characteristics of the ecosystem and human resource use activities is the top research priority of the BEST Program. The study of changing sea-ice dynamics and its impacts on ecosystem processes and sustainable harvests encompasses many of the individual processes important to the BEST Program. Furthermore, this is a particularly timely topic due to the changes recently documented in the eastern Bering Sea.

Atmospheric forcing largely drives ice formation and advection, but it is unclear how changes in wind patterns, precipitation, cloudiness, and storminess will affect the seasonality, duration, and distribution of sea ice over the Bering Sea shelf. Fluctuations in atmospheric forcing cause large (hundreds of kilometers) variations in the timing and location of the maximum extent of sea ice, the persistence of ice on the shelf, its thickness distribution, and polynya development. Furthermore, the maximum spatial extent of sea ice determines the size of the cold pool, a critical feature that influences the distribution of commercially valuable pollock and other fishes and benthic organisms. The cold pool also affects the metabolic rates of bacteria that regenerate nutrients to shelf waters. Since the characteristics and seasonality of sea ice presence strongly influence the timing, duration, and fate of primary production on the shelf, the mechanisms linking climate to ecosystem response cannot be fully addressed without understanding the effects of climate on sea ice. Thus, to evaluate how the eastern Bering Sea will react to changing climate conditions, we need a better understanding of how sea ice responds to variations in atmospheric forcing.

The presence or absence of sea ice affects water temperature, salinity, and baroclinic currents. Moreover, the formation, advection, and melting of sea ice influences heat and salt fluxes on the Bering Sea shelf. Ice formation produces cold, saline (as high as 34 p.s.u.) water through brine rejection, while melting removes heat and introduces cold (-1.7ºC), low-salinity water into the system. In the northern Bering Sea, the cold, highly saline water that sinks to the bottom is exported to the Arctic Ocean, where it strengthens the halocline. Thus, ice modifies the horizontal density structure, resulting in baroclinic currents that advect heat and salt over the shelf. During the past 40 years, there has been a trend towards a later onset of freezing, an earlier ice melt in spring, and a less persistent, thinner, and more patchy ice cover in the eastern Bering Sea.

Primary productivity in the eastern Bering Sea is strongly influenced by sea ice conditions on the shelf. The ice algal bloom is largely controlled by the seasonal light cycle, which is influenced by sea ice and snow thickness, and nutrient availability. In regions with seasonal ice cover, algal production within the sea ice appears to be a minor contribution to the total integrated primary productivity. However, the early timing of the ice algal bloom (weeks before increased production in the water column), and the resulting early input of released organic material during ice melt into pelagic and benthic ecosystems, might make this portion important for the production cycles of pelagic and benthic communities (Figure 2). While under-ice production has recently been observed at two moorings in the southeastern Bering Sea, this mechanism needs further investigation.

It is hypothesized that spring sea ice conditions influence the timing of the spring bloom, which is initiated by water column stabilization due to ice melt or solar insolation. The ecosystem effects of this variability in the timing and ice-association of the bloom likely include shifts in the fate of carbon between the pelagic and benthic components (Figure 2). For instance, changes in the dominant phytoplankton taxa, together with low temperatures, may result in low rates of secondary production and poor recruitment for secondary producers. In particular, characteristic ice-edge species such as certain heavily silicified diatoms and the Prymnesiophyte *Phaeocystis* spp. can affect the efficiency of transfer of primary production through the food web. In the Southern Hemisphere, rapid growth of *Phaeocystis antarctica*, coupled with extreme low temperature, results in very low direct trophic coupling between phytoplankton production and zooplankton grazing in spring and early summer. The generally low and variable species diversity of high-latitude phytoplankton blooms heightens the need to characterize phytoplankton community structure and to determine how food web responses vary in ice-covered, ice-edge, and ice-free conditions in the eastern Bering Sea. Phytoplankton species composition in the Bering Sea has undergone several unexpected changes over the past few decades, with blooms of coccolithophorids being the best-known example.

Similarly, the zooplankton community of the Bering Sea is composed of different micro- and meso-plankton components. The mix and interactions of these functional types is critical to the development of the Bering Sea shelf ecosystem in spring and early summer. Zooplankton production can be affected both by the abundance of prey and by the ability of the constituent species to assimilate food and convert it into biomass. In the southeastern Bering Sea, data on the accumulation and settling of phytoplankton suggest that primary production during the spring does not limit mesozooplankton grazing rates, though spring microzooplankton grazing rates have not been measured. Water temperature exerts a strong influence on growth rates of zooplankton and may be more important than food availability in limiting growth rates.

For poikilotherms, the rates of physiological processes, such as ingestion, assimilation, growth, and reproduction, generally increase with increasing temperature up to some maximum threshold that varies across taxa. At the same temperature, however, the metabolic rate of a cold-adapted species might be considerably higher than that of a warm-adapted species, even when these are closely related taxa. Changing metabolic rates impact the amount of energy available for the maintenance, growth, and reproduction of the zooplankton, and the coupling between trophic levels. Ultimately, these factors determine how much energy propagates into the upper trophic levels in the pelagic realm or sinks out to the benthic ecosystem. Reproductive rates of zooplankton can influence the early survival and growth of larval fish. Thus, ice-induced changes in zooplankton community structure and reproductive timing and rates may propagate through the food web as bottom-up forcing. Changes in the temperature regime in the Bering Sea have the potential to affect the growth rates of organisms from primary producers to top-level consumers in both the pelagic and benthic environments. Field experiments and models will need to consider the temperature sensitivity of phytoplankton growth, zooplankton grazing rates, and the functional responses of zooplankton and larval fish. Experimental studies and field observations will provide evidence for upper limits of metabolic rates (e.g., primary production, respiration, excretion) as functions of temperature, which ultimately regulate the growth of an organism.

Functional response characteristics of representatives of major functional groups of the marine web are important aspects of marine food web dynamics. Approaches for characterizing functional responses can include feeding experiments with modified prey densities and varying temperature and light conditions with different food sources. These experiments should focus on the dominant representatives of the major functional groups in the BEST study region. Other relevant studies of predator-prey dynamics include quantifying numerical responses (how the number of predators responds to changing prey densities), dietary shifts (how does predator diet reflect prey abundance and distribution), and changing spatial overlap (how do predators and prey overlap spatially and temporally). Such functional and numerical responses have important implications for understanding how the eastern Bering Sea will be structured in the face of climate change.

These bottom-up factors are expected to translate through the marine ecosystem of the Bering Sea, affecting the productivity, distribution, and abundance of fish, birds, and marine mammals. These upper trophic predators, in turn, fuel commercial and subsistence economies. For instance, hunting in ice leads, polynyas, and at the margins of fast ice provides seal, sea lion, walrus, and whale to Native communities from Bristol Bay to the Bering Strait. Additionally, travel over sea ice has been an important mode of transportation to and from hunting grounds and between communities. Loss of sea ice would significantly affect access to traditional subsistence foods, with an anticipated increased dependency on non-traditional foods and a shift to newly available open water species. Research is needed to understand the potential impacts of ice loss on hunting opportunities and the development of possible alternative food sources and economic activities in an ice-free eastern Bering Sea.

The commercial fisheries of the southern Bering Sea have been very successful, approaching the economic importance of the lucrative North Atlantic cod fisheries of the 19^{th} and 20^{th} centuries. Bering Sea fisheries currently employ thousands of fishers, processors, and distributors nationwide. Many Alaskans live around the eastern Bering Sea and depend on commercial fishing opportunities for employment. These ecosystem products are also critical for subsistence and for the preservation of cultural traditions. Climatic and ecological changes at the scale now observed pose many challenges to the inhabitants of the Bering Sea. It is likely that these ecological changes will benefit some resource users and harm others, with substantial socioeconomic implications for the region as a whole. The vulnerability of subsistence communities and commercial fishing activities to changes in the Bering Sea ecosystem remains a critical question.

2. Questions to be investigated in Module 1 may include the following:

a. How does external forcing affect the timing, extent, thickness, and coverage of sea ice?
The characteristics and extent of sea ice cover and the timing of its retreat play a major role in structuring the physical properties of the water column and in determining the timing and fate of primary production. To predict how climate variability will influence the sea ice, we need to know the relative importance of atmospheric forcing and ocean currents that transport heat. Atmospheric circulation patterns force local winds that can advect heat and melt ice at its southern extent or can cool surface waters and enhance ice formation in the northern Bering and advect ice southward. What are the relative roles of northerly and southerly winds, and which is more important in determining spring sea ice conditions in the eastern Bering Sea?

b. How does climate variability affect the transfer of primary production to the plankton and benthos, the fish, birds, cetaceans, and other upper-trophic predators on the shelf?

Carbon budgets. Climate variability will impact the amount and fate of the primary production within the ice and the water column. How are the total amount of primary productivity and the partitioning between ice and pelagic production different between warm and cold years? How do those alterations propagate through Bering Sea food webs and are these processes sensitive to the latitude at which they occur? Previous budgets for pelagic carbon cycling were constructed before the recognition that microzooplankton are the predominant grazers of phytoplankton in most of the world's oceans. What is the magnitude of microzooplankton grazing on the shelf? What fraction of primary production does this group consume during the spring bloom and during the summer stratified period? The Oscillating Control Hypothesis posits that temperature affects the ability of mesozooplankton to control an early spring phytoplankton bloom. Does temperature regulate the grazing impact of the microzooplankton as well? What is the effect of temperature on zooplankton growth, grazing, and reproduction? How would warming of the eastern Bering Sea affect carbon pathways? How do these processes in the water column affect the quantity and quality of organic matter settling to the bottom for benthic organisms, and their consumers?

Zooplankton production links to fisheries recruitment and production. Previous studies have examined the temporal linkage between zooplankton reproduction and larval fish survival. How does the loss of sea ice and shift in faunal boundaries affect the timing of prey production and spatial distribution of prey production for larval fish? Has the absence of sea ice and warmer water temperatures affected the occurrence of starvation among larval fish? Food web dynamics models (Ecosim/Ecopath) suggest the primary importance of euphausiid production and biomass on the growth and production by Bering Sea fish populations. They are also a key dietary component of whales and seabirds. In the 1970s and 1980s, euphausiids were a prominent component of the Bering Sea shelf ecosystem (70–90% of total spring shelf biomass; 15–30% of total spring slope biomass). Some recent work suggests that they are less abundant over the shelf than in previous years. Has the warming (both episodic and long term) of the eastern Bering Sea affected euphausiid distributions, vital rates, and population dynamics? Have these changes affected the distribution, abundance, diet, productivity, and demography of euphausiid predators? If so, is there evidence for changes in predator diets and/or distributions in the Bering Sea that have implications for subsistence and commercial harvests of upper trophic organisms?

c. Has the loss of ice cover in the eastern Bering Sea affected the structure and function of the planktonic and benthic communities by exposing the upper ocean to wind earlier in the season or for a longer period of time?

The loss of ice cover exposes shelf waters to wind earlier in the year and extends the period of air-sea transfers of heat and momentum. These changes in timing and seasonality modify at least three physical processes, which in turn affect the biological response of the shelf and shelf-break ecosystems: the extent of pycnocline formation and mixing, the position and strength of fronts, and the intensity of shelf-break upwelling.

Pycnocline depth and mixing. Prolonged deep mixing in late winter and early spring will favor growth of low-light-adapted species of phytoplankton in early spring. Will the growth of these species effectively reduce nutrient availability (and production) for (by) later blooms? Is the present spring stratification less intense than in years past due to the absence of fresh water from melting sea ice? How does changing the degree of water column stratification influence the rates of primary production? How do the vertical distributions of the various ecosystem functional groups respond to changes in the patterns of mixing and stratification?

Frontal locations. Three frontal systems, separating distinct water masses with their own pelagic and benthic communities, are major structural features on the eastern Bering Sea shelf. Will the loss of ice cover affect the geographical position and strength of these frontal systems? Will this change affect the ranges of the biota of the eastern Bering Sea? If the decrease of ice cover affects the strength of the frontal systems, will they become more or less permeable to exchanges of water and organisms among domains? If the loss of ice cover affects the strength of the frontal systems, will their importance as sites for biomass accumulation and increased productivity change?

Shelf-edge upwelling (and influence of transport across the shelf). The eastern Bering Sea shelf-break has been described as a “green belt” of enhanced production, supported by localized physical processes. Is shelf-break upwelling a regular occurrence in spring and early summer? Are slope species commonly advected onto the southern and central Bering Sea shelves? Has the abundance of large oceanic and slope copepods on the shelf changed? How would changes in the abundance of these large copepods impact the distribution, abundance, diet, productivity, and demography of upper trophic level predators? Will these responses differ for locally breeding and seasonally visiting predators? Does the abundance of large oceanic copepods over the outer shelf reduce predation pressure on juvenile fishes?

d. How does climate affect the balance of top-down v. bottom-up control of the zooplankton community?

Although bottom-up forcing of the zooplankton community has received much attention in previous Bering Sea studies, carbon budgets for upper trophic levels suggest that planktivores can consume all of the summer production and possibly all of the zooplankton standing stock. Can we quantify the sources of zooplankton mortality from above (fish, birds, and mammals)? Is there strong top-down forcing within the zooplankton (e.g., predation by jellyfish and chaetognaths) and the benthic (e.g., predation by epibenthic fish and invertebrates) communities? How does climate and loss of ice cover affect the fate and the rate at which secondary production is utilized within these ecosystems? Do the data from upper trophic organisms (e.g., diet, abundance, distribution, productivity, demographics, functional responses) support the hypothesized dichotomy between the predominant flux of primary productivity to the benthic and pelagic realms? How are these guild-specific responses related to remote (e.g., atmospheric forcing) and local (e.g., sea ice extent and timing) physical conditions?

e. How will subsistence and economic activities in the Bering Sea change?

How will the loss of sea ice affect access to traditional subsistence foods and dependence on non-traditional foods, including shifts to harvesting newly available open water species? How will the loss of sea ice affect subsistence activities, hunting, travel, diets, and economic opportunities for communities in the Bering Sea as a whole, as well as locally? Reduced sea ice might lead to a greater reliance on store-bought foods and economic opportunities outside of villages (e.g., in Anchorage or other distant cities). An ice-free ecosystem may also yield new economic opportunities locally, including enhanced pelagic fisheries. These impacts on humans from the loss of sea ice will likely vary in sign and magnitude across the region. Communities along the northern and central Bering Sea coast north of the marginal ice zone are particularly vulnerable because ice- and ice-edge-adapted species are central to their subsistence economies and cultures.

f. What will be the social implications of the changes in subsistence and economic activities in the Bering Sea?

Will the expected ecological changes impact certain social groups more heavily than others? What attributes make certain communities and groups more or less resilient to these impacts and opportunities? In what ways might these changes threaten and/or strengthen cultural integrity and tradition? How are subsistence and commercial activities vulnerable to change in the marine ecosystem? For instance, how might changes in the location of commercial fisheries modify access to employment, potentially changing reliance on subsistence harvesting? How might increased industrial activity in areas of new commercial potential (e.g., a northern expansion of the pollock fishery and establishment of new shore-based processing plants) generate unintended social changes or challenges? How will the loss of seasonally stable sea ice affect hunting, fishing, and travel? What implications could this have for subsistence-based cultural traditions as well as local economies? How could the introduction of new ice-free shipping routes through the Bering Sea and Arctic Ocean impact local communities, for example through increased hazards (e.g., oil spills, ship wrecks, lost cargos) and economic opportunities (e.g., construction of new ports of call)? How will these social and economic responses to climate and ecological change vary across the region?

g. How can studies of past climatic, ecological, and social responses to changes in sea ice extent and character illuminate present trends and future potentials?

Documentary and oral historical data provide high-resolution records of the variability in climatic and environmental change and human response occurring at interannual to centenary scales. These sources of information can increase the spatial and temporal resolution of variability around the Bering Sea prior to the availability of instrumental data collection and complement point source instrumental data once they became available. What do historic and prehistoric records teach us about dynamic relationships between climate warming and cooling, ecosystem change, and social processes? What do archaeological and paleo-ecological data tell us about climatic and ecological change in the past, at decadal- to millennial-scales? Evidence of ice-adapted or open-water-adapted species in midden deposits, for example, can be used to track past changes in sea ice extent. What can these records, preserved in archaeological deposits, lake and ocean cores, and related contexts, reveal about ecological dynamics during the last major sustained climatic warming episode for comparison to trends emerging in the current phase of warming? How did the seasonal sea ice margin expand and retreat in the past? How did people respond to these changes? What were the significant spatial and temporal scales of these responses? How did responses vary relative to factors such as mobility, technology, and social organization and connectivity? How have climate, wind, wildlife, and human adaptation and organization varied spatially and temporally at local spatial scales? What are the implications of these scales of variability for the vulnerability of the biota, humans, and marine ecosystems to environmental change?

VI. Scope of the Study and Observational Strategy

The BEST program is built around a mechanistic, question-driven approach. The strategy for studying the eastern Bering Sea includes: 1) multiple interdisciplinary cruises for the experimental investigation of processes, 2) long-term deployment of moorings containing the best available instrumentation for measuring physical forcing and chemical, optical, and biological properties, 3) intense satellite data acquisition of physical and biological conditions, 4) studies of past and contemporary human resource users and residents in their ecological and social contexts, and 5) improved models emphasizing the physical, biogeochemical, biological, and socioeconomic connections within the Bering Sea ecosystem and with the people who are dependent on it.

The scope of the physical and natural science components of BEST will provide an integrated perspective of the physical-chemical-biological linkages of the eastern Bering Sea ecosystem, from large-scale atmospheric forcing, through local physical forcing (e.g., wind, solar heating), through nutrients, primary production, zooplankton, and fish larvae to upper trophic level ecosystem constituents. Social science research will focus on past and contemporary communities of the eastern Bering Sea, including resident coastal communities, seasonal workers (e.g., fishers and freighters), and related industry groups and resource managers. Because the social science component is not constrained by ship-based logistics, we envision social science components expanding beyond this geographic range, for example to the Bering Strait region, as long as research is appropriate and suitably integrated with the other BEST research described in this implementation plan. Social science projects are expected to focus predominantly on coastal communities, fisheries fleets, shippers, and resource managers who work in or make decisions about the use of the eastern Bering Sea.

1. Interdisciplinary cruises

Research cruises will provide detailed and specific process-oriented data on the spatial and temporal distributions of physical and biological properties spanning four trophic levels, from primary producers (e.g., phytoplankton) to tertiary consumers (e.g., marine birds and mammals and fish). A grid of stations will be sampled during the spring and early summer seasons. This approach will provide a mechanistic understanding of how various interdependent processes control physical-biological coupling, productivity, and food web responses of the Bering Sea ecosystem.

The temporal and spatial scales of the natural science field research will be influenced by the duration of the initial module of the program (4 years) and by logistical limitations (e.g., ship-time availability). Given the expected duration of the field program, BEST will focus on interannual variability during spring (March–June) and will target the eastern shelf of the Bering Sea, from the Aleutians north to St. Lawrence Island. Previous sampling of this region will facilitate interdecadal comparisons of the effects of climate variability.

In the late 1970s and early 1980s the NSF program known as Processes and Resources of the Bering Sea Shelf (PROBES) intensively investigated the shelf and shelf-break region in the vicinity of mooring 2. In the context of climate change, it is essential that a subset of PROBES stations be regularly re-sampled in BEST to establish changes in community structure and productivity that have taken place over the past 25 years.

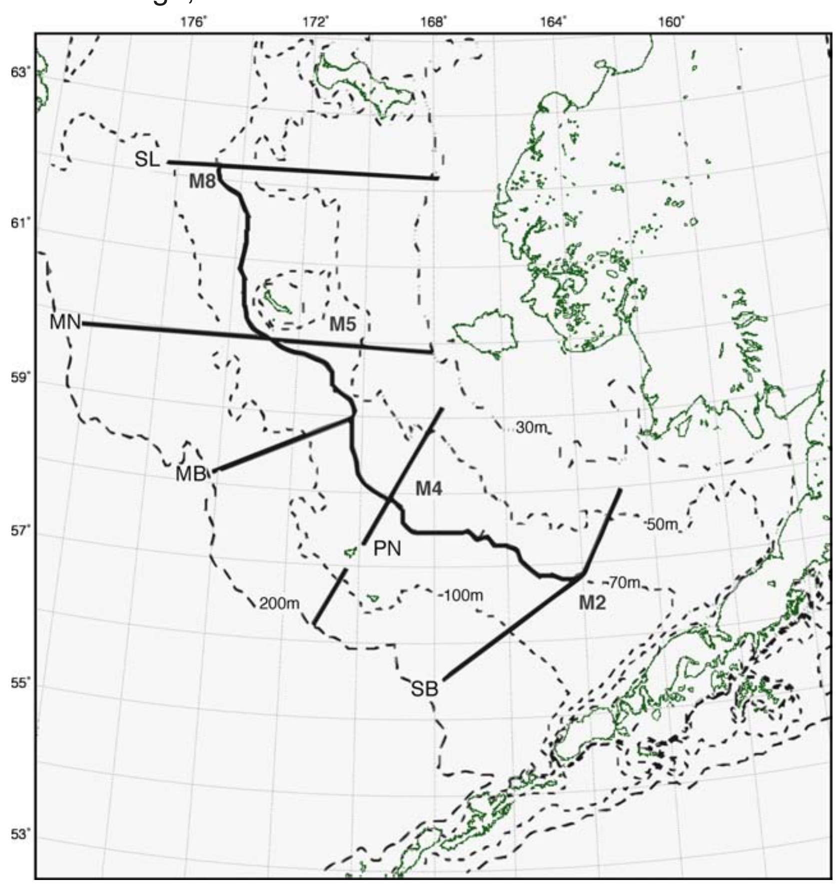

Figure 4. *Planned oceanographic activities in the eastern Bering Sea. Moorings M2, M4, M5 and M8 maintained by PMEL, NPRB and NOAA's NPCREP Program are located where the SB,PN, MN, and SL lines cross the 70-m isobath. Cross-shelf lines, extending from the inner shelf to the slope (500 m depth), are those planned for occupation in 2006, 2007, and 2008 by NPCREP (PMEL & AFSC). Figure courtesy of P. Stabeno (NOAA).*

2. Biophysical moorings

Moorings will provide continuous data on temporal and spatial variability of physical, optical, and biological properties. By embedding these mooring observations within the survey grid, BEST will obtain continuous fine-scale temporal data at specific locations before, during, and after the process measurements. This approach will provide a broader temporal context (e.g., conditions preceding cruise observations, interannual variability) for interpreting the process measurements and will facilitate the extrapolation of the daily process observations to monthly time scales. NOAA (Pacific Marine Environment Laboratory) currently maintains several biophysical instrumented moorings in the study area that could serve as the foundation for a larger observational network (Figure 4). Focusing the field program on this “strategic” area, will allow BEST to use the long-term time series of the present moorings (e.g., PMEL mooring M-2) and make comparisons to these and other historical observations.

3. Satellite remote sensing

Satellite data, ground-truthed to the extent possible with cruise and mooring observations, will be used to extrapolate the study conclusions to larger temporal (e.g., interannual) and spatial (e.g., Bering Sea shelf) scales. Remotely sensed ice extent and concentration observations will be augmented by ship-borne measurements of ice and snow thickness to determine under-ice light fields. Real-time access to imagery during cruises will be important for identifying and prioritizing unexpected sampling opportunities (e.g., sampling from coccolithophorid blooms). Thus, arrangements with NASA and NOAA for obtaining satellite data should be made well in advance to minimize cost. By integrating and assimilating these data into ecosystem and climate prediction models, we will assemble a mechanistic understanding of the response of the Bering Sea shelf to climate variability.

4. Upper trophic level studies

Coordination and integration of BEST activities with other agencies and research programs will provide information on the distributions, diets, and population trends of upper trophic level predators. The study of fishery resources will rely on research activities supported by the National Marine Fisheries Service, the North Pacific Anadromous Fish Commission, and the North Pacific Research Board, among others. Ongoing and past field work on marine birds and mammals by the National Marine Mammal Laboratory and the U.S. Fish and Wildlife Service, including at-sea surveys, tracking studies, and colony-based research on the diets, demography, and foraging effort of these upper trophic predators, will help place the year-to-year fluctuations in the at-sea distribution, abundance, and stress levels of marine birds and mammals observed during the BEST field program in a longer-term context.

5. Social science dimension

A suite of different techniques can be applied to understand the way human activities (e.g., subsistence harvesting, commercial fisheries) and communities respond to environmental variability. These approaches include archaeological, paleo-anthropological, and paleo-ecological research, the analysis of traditional knowledge and ethnographic information, and the study of economics (subsistence and cash-based), human demographics, public health, and resource management. Retrospective analysis of past climate regimes, ecosystems, and human-environmental dynamics will be possible by combining the results of studies of archaeology, paleo-oceanography, paleo-ecology, history, and local and traditional knowledge. Such projects should engage in interdisciplinary research that links humans of the past and/or present to the ecological dynamics surrounding changing sea ice conditions.

6. Modeling

The objective of the BEST program is to predict how climate change will alter future physical-biological-social conditions in the eastern Bering Sea. To this end, an ambitious synthesis and forecasting effort will be undertaken in conjunction with field activities (Figure 3). Modeling will focus on three research approaches: (1) retrospective analysis of the connections between local physical conditions and large-scale atmospheric variability, (2) assimilation of field data to gain a mechanistic understanding of local physical-biological coupling and biological-social coupling, and (3) forecasting of future climatic changes using predictions from coupled global climate models and the translation of their effects through coupled physical-biological-social models.

The assimilation of field data will allow the testing of models that relate how local changes in physical conditions influence the timing and extent of the spring phytoplankton bloom and the fate of primary production. These exercises will help to develop and refine the models needed to diagnose physical processes in key regions of the Bering Sea. Thus, data assimilation will help investigate model structures, determine the degree of model complexity necessary to depict accurately ecosystem processes, and specify the type and frequency of data that are required.

Simple and sophisticated ecosystem models with grazer-phytoplankton dynamics could then be linked to these physical models. To ensure that the relevant variables are measured with adequate temporal and spatial resolution and with the accuracy required for modeling purposes, modeling and field activities will develop hand-in-hand. Model development and testing will be undertaken before and after the field program, with additional data assimilation into process-oriented models during field activities. Synthesis models, which help to define knowledge gaps, may be suitable both prior to and after the field program. Forecasting models will be used to predict future conditions and may be feasible only after the necessary mechanistic data have been collected during the process-oriented field program.

Climate change scenario modeling should be an important focus for BEST modeling efforts, since it will extend the measurements of current conditions into the future. The use of the output of existing global coupled climate general circulation models forced by 21st century scenarios of greenhouse gas (GHG) emissions projections will be vital in predicting the regional response in the Bering Sea. Downscaling this predicted response, using eddy-resolved simulations of the Bering Sea, will facilitate comparisons of the current-climate conditions to semi-analogous past climate conditions and ultimately to future climate scenarios. Finally, by coupling models of local physical-biological conditions (optimized by data assimilation techniques) with the GHG-forced model predictions, potential long-term changes in the biology of the Bering Sea can be investigated. By coupling models of biological and social conditions, estimates of the implications of environmental change on human vulnerability can be explored.

Modeling will be a critical integration mechanism both within BEST and between BEST and other programs. Modeling is expected to form part of individual projects, as well as to contribute to cross-project and program-wide integration. Modeling should be part of an iterative process with the data collection activities influencing modeling and modeling results influencing future data collection. This iterative process between modeling and data collection has practical limits, given that the initial phase of BEST is expected to last four years. Thus, coordinated modeling and data collection should be initiated from the onset of BEST, so that tools and linkages are in place to maximize benefits to BEST beyond this initial phase. Techniques of data assimilation, comparison of alternative models, and sensitivity and uncertainty analyses should be considered in the modeling effort. While each modeling project will need to decide on the appropriate temporal and spatial scales for their specific questions, there should be consideration towards developing 5- to 10-year forecasts for the major regions within the eastern Bering Sea. As much as possible, common climate scenarios should be simulated across models to facilitate comparative studies and integration across projects.

VII. Implementation Activities

A. Observational Studies

1. Cruises

The BEST survey and process cruises will be conducted annually during spring (March–June), over a three-year investigation. To contrast the ecosystem structure of and response to ice retreat, the ice edge, and ice-free conditions, we anticipate the need for two ships (an icebreaker in the northern Bering Sea and an ice-strengthened vessel in the southern Bering Sea) that will be deployed simultaneously. The specific stations and tracks will be selected as a balance among practicality, justification for specific studies, and continuity and consistency with previous and ongoing field sampling in BEST and other research programs. We envision that sampling will generally involve each of the vessels surveying a predetermined grid of stations including the shelf-break, outer shelf, middle shelf, and inner shelf. Overlap with previous and concurrent survey tracks, such as those planned to be occupied by NPCREP, will be an important consideration (see section VI.1). On these cruises, two types of stations are anticipated: survey stations, at which a limited number of observations will delimit the spatial and temporal distributions of physical and chemical properties and the distributions of species, and process stations, at which additional detailed process studies will be carried out.

Pending the number and types of funded proposals, BEST field activities will include:

- 2 ships: 4 months/3 months
- Month-long cruise legs
- Turn around at the ports of Dutch Harbor and/or Nome
- Concurrent work in the north (ice) and south (open water)

Following the collaborative, multi-investigator approach previously adopted by the JGOFS and Southern GLOBEC programs, individual proposers will request ship-time to participate in specific field activities, and funded investigators need not work at all sites or during all cruises. To ensure the effective collaboration of different investigators and proposals, the different research groups will be encouraged to complement each other's activities. Integration of data from the two ships will be facilitated by adopting common standard methods (station numbering scheme, basic survey plan, methods of sample collection, experimental protocols).

Observational synergy between BEST and other field programs. The BEST field program is designed to leverage an extensive array of oceanographic measurements that will be made by other programs in the next few years. These observational programs will be supported by NOAA's North Pacific Climate Regimes and Ecosystem Productivity (NPCREP) program and by the North Pacific Research Board (NPRB). An example of the synergistic sampling planned during the BEST field activities is shown in Figure 4. At present, it is expected that PMEL will have at least 4 biophysical moorings located along the 70 m isobath.

These mooring data will be supplemented with standardized stations along 5 onshore–offshore survey lines (A, B, C, D, E) extending from the inner domain to the continental slope (500 m depth) connected by a section along the 70 m isobath that could be occupied by BEST cruises.

Because of sea ice considerations, moorings will likely be changed out twice annually, with surface and near-surface instruments being precluded in winter. Moorings in the ice-free season will likely include instrument packages at 5, 10, 20, 50 m depths, as well as on the bottom. Some moorings may have a set of meteorological instruments on a surface float. The sensors in the instrument packages could include, but are not limited to:

- Conductivity and temperature sensors
- Chlorophyll (fluorescence) sensors
- Nutrient sensors
- Dissolved gas sensors
- Phytoplankton and zooplankton collectors and sensors
- Sediment traps
- Irradiance sensors
- Particle sensors

In addition, the BEST program will most likely require additional moorings in the inner and outer domains to capture variation in the cross-shelf axis. Other sampling layouts are possible, within the logistical constraints of the available sampling effort, the need for multiple investigators to share ship time, and the desire to ensure continuity with past and future data collection.

Suggested Core Observations by BEST Survey and Process Cruises. This suite of data is considered the fundamental data set that should be acquired whenever the ship is underway between stations or moving within the study area.

<u>Meteorological Observations</u>

- Wind speed
- Wind direction
- Humidity
- Sea-surface temperature
- Air temperature
- Incoming shortwave radiation
- Outgoing shortwave radiation
- Photosynthetically active radiation (PAR)
- Barometric pressure
- Precipitation
- Sea ice conditions
  - Percent cover
  - Ice thickness
  - Ice type
  - Snow cover and thickness

<u>Hydrographic Observations</u>

- Conductivity
- Temperature
- Oxygen
- Nutrients
- Fluorescence

<u>Biological Observations</u>

- Marine birds
- Marine mammals
- Presence of discolored water or ice

Suggested Observations at Standard Survey Stations. In addition to the set of underway measurements, the following suite of observations is considered the fundamental data set that should be acquired at all stations during cruises to the eastern Bering Sea.

<u>Hydrographic Observations</u>
(Depth-resolved)

- Conductivity
- Temperature
- Oxygen
- Nutrients
- Pigments
- Fluorescence
- POC
- DOC
- PON
- PAR
- Total CO_2 and alkalinity
- Ice and snow thickness

<u>Standing Stocks</u>
(Selected stations and depths)

- Phytoplankton composition and biomass
- Ice algae composition and biomass
- Microzooplankton composition and biomass
- Mesozooplankton composition and biomass
- Larval fish composition and biomass

Suggested Observations at Process Study Stations. Intensive, process-focused stations should include all observations made at a standard survey station. In addition, intensive process stations can include specialized observations that will reflect those processes deemed critical to understanding controls of flux rates through different compartments of the ecosystem. These process observations should be made consistently at all intensive process stations during the program to facilitate spatial and interannual comparisons. Additional measurements that could be made include: direct measurements of carbon:chlorophyll ratios, phytoplankton division rates, coccolithophore growth and calcification rates, productivity of mesoplankton, microplankton, and bacteria, and nutrient remineralization in sediments.

Rate Measurements

- Primary production (carbon)
- New and regenerated production (nitrogen and silica)
- Production and respiration (oxygen)
- Microzooplankton grazing and growth
- Mesozooplankton grazing and growth
- Larval fish grazing, growth, and condition

2. Biophysical moorings

NOAA (Pacific Marine Environment Laboratory) currently maintains several instrumented moorings in the study area that could serve as the foundation for a larger observational network (Figure 4). Four moorings are currently active in the southeastern Bering Sea (M2, M4, M5, M8). These moorings are serviced twice yearly by NOAA. While currently there are no means to retrieve the mooring data in real time, data retrieval with telemetry may be available in the future.

3. Satellite remote sensing and *in-situ* ground-truthing

Sea ice extent and concentration will be observed using available passive microwave remote sensing data (SSM/I and AMSR-E). Observations of sea ice and snow thickness are important to estimate thickness and volume changes and their effects (e.g., light penetration). Ice thickness can be observed from a combination of upward-looking sonar mounted on existing or future moorings and by measuring ice thickness from ship- and helicopter-based surveys using electromagnetic (EM) induction techniques. Collection of *in situ* ground-truth data in terms of hand-drilling for sea ice thickness and measuring snow depth and other surface properties is important for interpreting the remote sensing and EM-derived data. Biological measurements on sea ice may include estimates of nutrient concentrations, ice algal biomass and productivity similar to the water column collections. Collaboration with local monitors from communities and fishing operations (Local Observation Networks) may provide opportunities to enhance spatial and temporal coverage of ice conditions in the eastern Bering Sea.

4. Upper trophic level studies

Studies of upper trophic levels will include at-sea observations of marine birds and mammals on cruises, as well as studies of indices of stress, reproductive ecology, and food habits at colonies and rookeries. Studies of adult fish distribution, abundance, growth, and diet are routinely undertaken by the NMFS during standard summer annual bottom trawl and biennial midwater acoustic surveys. BEST researchers wishing access to these data will need to establish collaborations with the scientists responsible for the surveys. Research on recruitment mechanisms and life history of fish (e.g., larval fish distribution, ecology, and survival) may be undertaken during BEST research cruises. It is anticipated that collaboration with NMML and FWS scientists will be important for marine bird and mammal studies within BEST (see section IV.1).

5. Social science dimension

Social science field studies will focus on past or contemporary communities located in the eastern Bering Sea region that were or are most vulnerable to the shift from seasonal sea ice to ice-free conditions. Data collection should document economic relations (subsistence and cash-based) and social and cultural importance of sea ice and its seasonal variability. Research to some extent should be driven by and contribute to modeling of the human environmental dynamics surrounding changes in sea ice distributions. It is expected that this research will be developed in coordination with the data collection and modeling tied to the oceanographic and marine ecological studies of the survey and process cruises or related studies of upper-trophic dynamics. Synthesis of social science analyses with the natural science analyses is an expectation of an integrated product upon conclusion of the BEST field programs. Potential social science observations and activities will include:

- Subsistence activities
- Economic activities (monetary)
- Demographic structure
- Public health challenges, mechanisms, and social safety nets
- Linkages between social structure and subsistence and cash economy
- Linkages between economic opportunity and use of the Bering Sea
- Resilience or vulnerability of community structures to ecological change
- Resilience or vulnerability of community structures to external policy decisions
- Uses of sea ice, time spent on sea ice, attachment to lifestyles involving ice
- Archaeological sampling of middens for paleo-ecological and climate data
- Archaeological sampling of middens and occupations for data on human adaptations
- Documentary analysis
- Local and traditional knowledge interviews
- Community partnerships

Social science studies will use a variety of information sources to study possible impacts of retreating sea ice on Alaska Native and non-native residents, itinerant commercial fishing and shipping communities, and resource managers. These social science perspectives contribute to the same three components found in the natural science structure: retrospective field and lab studies, field studies of contemporary communities, and modeling efforts. Information sources for these social science efforts may include:

- Archaeology and paleo-ecology
- Local and traditional knowledge
- Ethnographic observations and responses to survey questionnaires
- Subsistence and fisheries catch records
- Demographic data (births, deaths, migration, age and gender)
- Resource management goals and practices
- Human ecological, economic, demographic, and social models

Archaeological, Paleo-anthropological, and Paleo-ecological Research. Archaeological data can extend historical analysis of environmental change and human response back across times scales longer than available historical and instrumental records. Paleo-anthropological studies can be used to identify past changes in diet and health, migration and relative isolation. Paleo-ecological studies complement archaeological research and include retrieval and analysis of pollen cores, tree rings, animal and plant remains (in or out of archaeological deposits). Moreover, coastal geomorphology and stratigraphy can help reinforce archaeological analyses, providing proxy data for past climate regimes.

Traditional Knowledge. Native and non-Native residents and users of the Bering Sea have developed extensive place-based knowledge about Bering Sea physical and ecological dynamics and change. Traditional knowledge collection and synthesis requires the cooperation of knowledge holders who are most willing to share their insights when they can expect a beneficial outcome from that sharing. Social scientists and resident communities have been successful in developing "ecological knowledge cooperatives." These are designed through respectful collaboration, in a model in which knowledge is not "captured" or "taken" from the community, but rather shared and developed into mutually beneficial databases. These data can be used for community purposes as well as for integration with other scientific data sources. We recommend that mechanisms be built into BEST for the formation of an ecological knowledge cooperative to coordinate the integration of traditional knowledge and BEST natural science within resident communities. We also recommend that a similar information cooperative or network be established in fishing communities.

Ethnographic Analysis. Ethnographers study communities through participant observation, individual and focal group interviews, and linguistic analysis. These methods can reveal information relating to the organization of activities, interactions in social, political, and economic networks, and the structure of value systems that guide proximate decisions and actions. Related to BEST, ethnographic research could focus on subsistence practices, engagement in wage employment, investment strategies, travel over land, sea and ice, and the importance of these and other activities to communities. A relatively unexplored domain of ethnographic research that should be encouraged within the BEST framework is the study of the commercial fishing industry, which includes both Native and non-Native fishers.

Economic Analyses and Modeling. To understand the implications of environmental change on communities of Bering Sea users requires collection, analysis, and modeling of economic conditions, networks, and structures. Changes in ecological conditions are expected to force changes in redistributive mechanisms and structures of economic opportunity. Ethnographically sensitive economic models need to be developed and coupled to ecosystem models to improve understanding of the implications of expected or possible future environmental conditions on subsistence and commercial users. These models should also seek to predict conditions that might provoke increased or decreased human impacts on natural systems (e.g., increasing numbers of fishing boats in the Bering Sea to take advantage of greater fishing opportunities might result in elevated pollution and bycatch, while loss of price for fishing and a depressed fishery would have the opposite effect).

Demographic Analysis and Modeling. Related to economics, research is needed to understand changes in the demography of the Bering Sea communities (residential and seasonal). Important to the question of the survival of rural lifeways in the Bering Sea is an understanding of the basic structure of communities—marriage and migration, birth and death rates, sex and age profiles—as these relate to cultural values and economic opportunities. Demographic models are needed to synthesize key population variables that can be coupled to economic models, and used to understand interrelated responses and plan for desirable outcomes.

Resource Management Scenarios. Subsistence and commercial activities in the Bering Sea, like elsewhere in Alaska, are heavily managed at the national and state level by processes that are at best marginally sensitive to social variability, or cultural difference. Studies of processes of resource management and models of their implications for different communities of users under changing environmental conditions are needed.

Public Health Implications of Bering Sea Change. Changing natural and social systems are likely to affect the health and welfare of Bering Sea residents and non-resident users. Changes in access to quality subsistence foods, for example, have significant implications for public health, especially where economical replacement foods might be of lower quality (e.g., junk food), or where subsistence foods may become more contaminated. Likewise it would be important to study the infrastructure capacity of rural Alaska to support health care under changing demographics and economics driven by a changing Bering Sea ecosystem.

B. Modeling Studies

BEST will consider a broad hierarchy of models that link large-scale climate forcing of regional oceanic response to the impact of ecosystem changes on societies. Some of these modeling techniques currently exist, while others may be conceived and developed as part of BEST. In general terms, four modeling components are needed for synthesis and integration:

- Global coupled ocean-ice-atmosphere climate models of current and future climate, to place regional forcing effects in a large-scale context;
- Regional coupled ocean-ice-atmosphere-ecosystem model simulations, to downscale the influences of physical climate forcing on biological systems at high resolution;
- Localized process-oriented models, to address the detailed coupling of physics and biology and to optimize the predictive ability of this new information for changes in local variables;
- Social science (e.g., economics) and fisheries (e.g., multi-species or single species population) models to investigate the effects of ecosystem variability on human systems.

Physical models will be a critical aspect of BEST, enabling broader spatial and temporal interpretation of BEST field data, hindcasting of Bering Sea conditions, integration of BEST observations with other historical and concurrent research programs, and forecasting future conditions under assumed climate change scenarios. Examples of relevant physical models include those dealing with ocean circulation, ocean-atmosphere coupling, and sea ice dynamics. In particular, the availability of coupled ocean-atmosphere-sea ice models for the Bering Sea is critical to the success of the BEST program. Existing models for the Bering Sea or other systems could be modified and tailored for use in BEST. Alternatively, new models could be developed. Assimilation methods will help to identify robust model structures and critical uncertainties associated with field sampling.

Biological modeling can involve both ecological and human aspects of the ecosystem. Ecological models coupled to circulation models include those that represent nutrients-phytoplankton-zooplankton, coupling of the pelagic and benthic environments, and simulation of larval fish movement, growth, and mortality. Other ecological modeling approaches include spatially-explicit food web models, bioenergetics growth and feeding (e.g., functional response) models, recruitment models, and the expansion of population and food web models of key species to include more detailed physical forcing explicitly. Bioenergetics models provide a good way to integrate experimental and field observations for specific taxa. Moreover, the availability of bioenergetics models for representative species from different trophic levels provides a framework for integrating across different disciplines.

Food web models, which could provide baselines for investigating current conditions and for scenario testing responses to climate variability, should include humans from the start. Additional human-related biological models could include social network analysis, agent (individual)-based approaches, demographic models, and economics-based models. These models would be used to understand how changes in ice dynamics cascade through the ecosystem (e.g., aquatic food web changes, increased wave erosion, altered fresh water supply, changes in shipping and transportation, restriction of traditional human mobility, altered spatial and temporal distributions of biota), affect human dynamics and their interrelationships.

The coupling of physical, ecological, and human-related models is greatly needed, and

BEST offers an excellent opportunity for the development of coupled physical-ecological-human models (Box 1). The coupling between models can be one way (output of one model used as input to another model) or fully dynamic (e.g., people responding to ice-induced changes in fish and mammals, which in turn, affect the dynamics of the fish and mammals). The development of project-specific models useful for integrative analysis, as well as the development of coupled models, will require careful planning, frequent communication, and research into the scaling issues involved in meshing the various linked models.

VIII. Provisional Implementation Schedule

1. Field Schedule

Detailed planning of field studies should begin as soon as funding decisions are made (anticipated in early 2006). Present planning suggests that field studies will be conducted in 2007–2009. Finding and scheduling adequate ship support is a priority. In each field season, there will be a need for an icebreaker from 1 March through May, and a second, ice-strengthened vessel from 1 March through the end of June. Both vessels will have to be sufficiently large to accommodate a science party of 20 or more. Both vessels, and in particular the ice-strengthened vessel, will need to have good sea keeping ability in Beaufort 5–6 conditions. The proposed Alaska Regional Research Vessel that is to replace the R/V *Alpha Helix* would be an excellent choice, but until it is built, it may be necessary to charter a suitable vessel. BEST scientists may also be able to piggyback on cruises supported by other agencies (e.g., NOAA) to supplement sampling from the two BEST UNOLS vessels.

Simultaneously, social science research should be planned to include broad coordination and collaboration with resident communities, villages, transient populations (e.g., commercial fishers from outside the area), managers, and others to ensure appropriate permissions and ethical protocols are established and followed.

Cruise and land-based field studies should include constructive engagement with resident village populations in the region of study. In addition to introducing the field research to community representatives, plans should be established for the subsequent distribution of project results in digestible form to interested communities.

2. Modeling Studies

It is recommended that modeling studies be initiated as soon as possible, i.e. 2006, following recommendations provided above. This will be particularly important for site-specific models, the results of which may influence the design of field studies.

Development and validation of the various components of the regional ocean-ice-atmosphere-ecosystem model will coincide with the organization and execution of the BEST field program. Although some of these modeling components may already exist or be developed independently of BEST, the models that are used in BEST must be carefully constructed in a framework that will be suitable to address the BEST goals. This will likely involve retrospective hindcasts using seasonal cycle forcing, including observed wind stress, heat flux, and freshwater flux forcing over key time intervals, such as the recent period of rapid ice loss. As these models are constructed and validated with historical observations, they may prove helpful to test or guide BEST sampling strategies in Observing System Simulation Experiments.

Once the BEST observations are in hand, targeted data assimilation experiments with the physical observations will be required to synthesize the results. This will likely involve sophisticated techniques such as four-dimensional variational assimilation. The results will allow diagnosis of the balances of the physical dynamics and provide a benchmark model result for understanding which physical elements control observed ecosystem responses. The results of the data assimilation experiments will also allow a comparison with retrospective hindcasts for understanding long-term changes in the BEST domain. Physical hindcasts of the BEST observational period can then be used with various ecosystem models to improve understanding of ecosystem responses to physical forcing.

The integration between the natural science dimension (which emphasizes the lower trophic levels) and the human dimension (which emphasizes the upper trophic levels) of the BEST program will be accomplished through modeling, acknowledging that the data required to address the broad fishery and social implications of climate change must be obtained from agencies (e.g., NOAA, ADF&G, USFWS) currently gathering these data. The integration of the social and natural science components will require effective mechanisms for information exchange, including P.I. meetings and joint symposia to disseminate research results.

3. Synthesis Activities

BEST is envisioned as having two four-year components with the first three years of each emphasizing data collection and field activities and the fourth year devoted to synthesis. While BEST will have a strong modeling component oriented to articulating the dynamic relationships between physical, biological, and social variability from the onset, the synthesis activities will emphasize modeling and integration. Researchers will be encouraged to synthesize data from other research sources such as subsistence studies, commercial fish counts, and published ethnographic and historical documents. While field research may include any relevant social or natural science approach, it should be linked through interdisciplinary partnerships and modeling to explore physical-biological-human interactions and ecological and social dynamics (Figure 3).

IX. Management Structure

BEST is guided by an Interagency Oversight Committee comprised of representatives of federal agencies concerned with research in the eastern Bering Sea region. At present, it is envisaged that BEST will have a Science Steering Committee, within which there is an executive committee of three or four individuals, including the Chief Scientist. It is expected that there will be a small project office, with the Chief Scientist and an assistant who can act as an Executive Director, and can represent the program when the Chief Scientist is unavailable. It is anticipated that, for the present, logistical arrangements will be provided through the Arctic Research Consortium of the U.S. (ARCUS). Depending on the eventual size of BEST, it may be useful to have working groups of P.I.s and outside investigators focused on issues such as Modeling; Data Management and Archiving; and Integration, Synthesis, and Outreach.

To fully achieve the goals of this implementation plan, it will be critical to establish and maintain collaborative observation and knowledge sharing networks involving BEST researchers and Bering Sea residents, both year-round and seasonally. We believe that this will require the establishment of a dedicated team of individuals to assist in three areas: 1) coordinating community-based data collection (e.g., ice thickness monitoring around villages, sea surface temperature readings from fishing vessels); 2) facilitating culturally appropriate and ethical collection of traditional knowledge relevant to physical, biological, and social characteristics of the Bering Sea ecosystem; and 3) developing appropriate channels and venues to communicate scientific research results to Bering Sea communities for their planning needs. This management team should include community representatives and scientists (physical, biological, and social) with a mandate to ensure the mutual benefit of collaboration to all parties. Mechanisms could include: 1) school-based data collection and scientific education; 2) development of community-based models for traditional knowledge interviews and database construction as well as processes for consent to use this information for scientific purposes; and 3) community seminars for the presentation, translation, and reflection of BEST results to relevant community groups.

X. Data Policy

BEST seeks to promote a collaborative atmosphere in which investigators share their data freely with each other and with the broader scientific community. To promote this exchange of data, the observations and measurements gathered during the BEST program will be handled in accordance with established funding agency guidelines for data reporting, archiving, and management. Because BEST is an integral part of both the Ecosystem Studies of Sub-Arctic Seas (ESSAS, a regional program under the International Global Ocean Ecosystem Dynamics [GLOBEC] program) and the Study of Environmental Arctic Change (SEARCH, an interagency effort by several U.S. agencies), data management within BEST will conform to the data management policies of these programs. Additionally, GLOBEC is a component of the Scientific Committee on Oceanic Research (SCOR) and the International Geosphere-Biosphere Programme (IGBP). Thus, the BEST data policy will be in accordance with the approaches sanctioned by GLOBEC (www.pml.ac.uk/globec/data/data.htm), SCOR (www.jhu.edu/~scor/DataMgmt.htm), and SEARCH (www.arcus.org/search).

The BEST data policy is designed to maximize the dissemination of information and the sharing of resources with other researchers and data archival programs. This data policy assumes that the BEST project will be managed through a central Project Office (PO; see section IX), which will ensure the effective management of the BEST field data and metadata (see Table 1). Working in conjunction with ESSAS, GLOBEC, SEARCH, and the Arctic Research Consortium of the United States (ARCUS), the BEST PO will implement a flexible data management system, relying, to the fullest extent possible, on existing data archival infrastructure and distributed data systems. BEST investigators will be required to contribute descriptions of the data collected with support from the BEST program to a central database at the PO, which will provide an inventory of data collected, and a record of the disposition of these data. After a two (2) year period—starting on the date of data collection—of proprietary use by the investigators within the BEST program, BEST metadata and data will be made available to the broader scientific community and deposited at an appropriate data archive decided upon in consultation with the funding agencies. Data centers relevant to BEST include the NOAA National Oceanographic Data Center (NODC; www.nodc.noaa.gov), the NASA Global Change Master Directory (GCMD; gcmd.gsfc.nasa.gov) and the Ocean Biogeographic Information System (OBIS; www.iobis.org).

Effective data management will require the cooperation of the entire BEST science community. All investigators involved in BEST field activities will make available an inventory of surveys and field sampling and data processing accessible to the PO in digital format. Within three (3) months after completion of a cruise or field season, the chief scientist—in cooperation with the participating principal investigators—will submit a detailed inventory of all physical and biological measurements made during a cruise or field season. This inventory will include the time (standardized cruise/expedition number, date) and the location (standardized station number, latitude, longitude), of each measurement as well as a schedule for submission of full or partial data sets to the appropriate data center. Within six (6) months after completion of the cruise or field season, investigators will provide to the PO, in digital format, supplementary inventory information for those samples requiring manual sorting and computer-intensive processing. Special attention will be given to the inventory of biological samples and to the compilation of the types of analyses planned for these samples. All information necessary to track and retrieve a specific sample—as well as any subsamples taken—

must be made accessible to the PO.

Table 1. Categories of data and metadata and their processing within BEST. Modified from the data access policy of the Georgia Coastal Ecosystem LTER, http://gce-lter.marsci.uga.edu/lter/research/guide/data_access.htm

Category	Source	Description	Maximum waiting period	Destination
Inventory 1	Chief Scientist	Inventory of field sampling	3 months	PO
Inventory 2	Individual investigators	Inventory of sample processing	6 months	PO
Data 1	Hydrographic/oceanographic investigators	Preliminary hydrographic/oceanographic data	At end of cruise	All PIs on cruise
Data 2	Hydrographic/oceanographic investigators	Final hydrographic/oceanographic data	6 months	All PIs on cruise, then data archive
Data 3	Individual investigators	All data, metadata, and standard analyses	2 years	Data archive

Investigators will be expected to make their data available to other BEST researchers in a timely fashion. Basic hydrographic/oceanographic measurements (e.g., temperature, salinity, oxygen, nutrients, chlorophyll, transmission, PAR) must be made accessible to the PO upon the termination of a cruise and experiment. Following precedents established in the U.S. Joint Global Ocean Flux Study (JGOFS) program, the U.S. GLOBEC program, the U.S. Northeast Water Polynya (NEWP) program, and Western Arctic Shelf-Basin Interactions (SBI) program, fundamental oceanographic data including temperature, salinity, oxygen, and nutrient distributions will have initial quality assurance/quality control (QA/QC) procedures performed onboard the research vessels at sea, thus allowing all principal investigators to depart each cruise with a DVD containing these preliminary data. Once additional quality control procedures have been performed ashore, the BEST component responsible for the hydrographic/oceanographic data sets will release a final version of these data as soon as possible and no later than six (6) months following a cruise.

All data and any derived standard analyses will be deposited in digital format in a publicly accessible data archive within two years (24 months) after collection. Standard analyses might include the displacement volume and vertical profiles of net tows, displacement volume and grain size distribution of sediment trap samples, and any other similar derived metadata useful for interpreting these observations. It is not a requirement, however, that these standard analyses be conducted. The principal investigators are responsible for selecting which types of analyses are appropriate for the scientific objectives of each experiment. We expect that these analyses will be specified in BEST proposals and planning documents. Metadata describing analyses similar to those listed above and produced from BEST-supported sampling must be submitted to the data archive. Relevant metadata must include all data necessary for interpreting a sample, including sampling methods, weather conditions at the time of sampling, and all procedures that were followed to collect the samples, analyze the samples, correct errors, remove noise, or otherwise modify the collected data. Modeling studies should also make their model runs and relevant metadata available to the data archive by the end of this two-year time horizon. The two-year period of proprietary use may be extended in circumstances where samples or data require extensive processing. Social science data require different management protocols to ensure compliance with human research guidelines and subject confidentiality. The exact data sets and their handling specifications will be determined, in consultation with funding agencies, by the group of principal investigators eventually funded in the program.

To promote interdisciplinary collaborations, it is expected that any BEST investigator using observations (field data, model results) collected by another investigator in the program will offer co-authorship to the individual(s) who collected these data during the two-year proprietary time-frame. Although the basic hydrographic/oceanographic data have come to be termed "service" data, they are to be treated in the same manner; principal investigators collecting temperature, salinity, oxygen, nutrient, and chlorophyll data should be offered co-authorship on manuscripts using those data. After the two-year period of proprietary use, investigators from within and outside the BEST program are urged to use the resulting observations in a courteous and collegial fashion.

A primary purpose of the BEST data inventory will be to facilitate collaboration among scientists for interdisciplinary and comparative studies. Any researcher making substantial use of BEST observations must acknowledge in presentations and publications the investigators who acquired the data, the BEST program, and the funding agency that supported the data collection. Additionally, investigators are also encouraged to offer the original collectors of these data co-authorship of publications when appropriate. This courtesy extends to field observations, model results, and data compiled for retrospective analyses. As possible, the BEST PO will encourage and facilitate the ethical and collegial use of the BEST data sets.

Investigators within and outside the BEST program should notify the BEST PO of any published papers making use of BEST observations. For publications supported in whole or in part by BEST funding, a BEST publication number will be assigned by the BEST PO, which will maintain a bibliography and set of PDFs of all BEST publications. This publications list will facilitate documentation of the contributions of BEST and the development of syntheses.

Appendix 1. Additional Research Modules

Additional research questions important to our understanding of climate-impacted processes that may influence the ecosystems of the eastern Bering Sea have been developed in four ancillary modules. Like the core BEST program outlined in Module 1, these questions aim to increase our understanding of the oceanographic factors and mechanisms that help predict ecosystem and social responses to climatic variability in the Bering Sea.

These four additional research modules, which focus on subsets of the issues raised in Module 1, overlap and complement each other. Each contains substantive questions of high scientific importance that could not be addressed in the core BEST program. Thus, they have been devised to provide research questions for a larger BEST program, once Module 1 has been adequately addressed. The BEST SSC will develop Implementation Plans for these modules in the future.

Module 2: Water temperature and ecosystem response

Recent evidence shows that the eastern Bering Sea is warming, and since 2000, water temperatures in both winter and summer have been higher than previously recorded. A dramatic and widespread response of the Bering Sea, and the entire Arctic, to warming may be a northward shift in range boundaries for many species. Range expansion or migration has been documented on land and in the ocean, in both plant and animal taxa of Alaska. The Bering Sea is a transitional area between sub-arctic and arctic regions; there is now the possibility that the Bering Sea is becoming incorporated more completely into the sub-arctic biogeographic province. Large latitudinal shifts in the ranges of oceanic flora and fauna will have dramatic impacts on the ecosystem structure and inhabitants of the Bering Sea and adjacent regions, such as the Chukchi Sea, Beaufort Sea, the Canadian Basin of the Arctic Ocean, by disrupting the distributions and predictability of the food webs and marine resources in these areas. If the Beaufort and Chukchi stay in the arctic province, then what will change? One thing may be that mobile predators that rely on arctic prey may become more concentrated in the Arctic until compensatory mechanisms affect their numerical response. As water temperatures and thermal stratification have changed, nutrient resources and competitive interactions in the phytoplankton are changing in ways that may have contributed to the unexpected coccolithophorid blooms observed in the late 1990s. In addition, latitudinal shifts in living marine resources are predicted to have socioeconomic costs associated with the redistribution of commercial species, creating new interactions between commercial and protected species that currently do not exist, and altering recruitment in commercial species that lose preferred habitat. The relative importance to these range shifts of changes in winter sea ice cover and sea temperatures versus warmer, more stratified conditions in summer need to be investigated and the ecosystem and socioeconomic consequences of these range changes understood.

Module 3: Processes controlling nutrient replenishment over the shelf and their sensitivity to change

The levels of macronutrients on much of the eastern Bering Sea shelf are depleted in surface waters by mid-summer. This is in sharp contrast to the oceanic regions of the Bering Sea in which relatively high levels of surface macronutrients remain year-round. Continued new production on the shelf, therefore, ultimately depends on the yearly renewal of macronutrients to the surface. Prior sampling has identified two sources for nutrient renewal, the rich supply of deep-water nutrients on the slope and the regeneration of nutrients in shelf bottom waters. At steady state, these supplies must balance the loss of nutrients through the Bering Strait and by processes, such as denitrification, that are prominent in shelf sediments. Beyond this basic mass balance, however, we lack detailed information on the identification and relative role of processes that restore shelf macronutrient levels and the extent to which these processes are sensitive to climatic forcing. For example, despite its low temperatures, a significant amount of nutrient regeneration takes place in the shelf cold pool as reflected by increasing levels of ammonium and phosphate and decreases in oxygen. How does this regenerative flux vary as the extent and temperature of the cold pool varies? Are all nutrient fluxes a simple function of temperature, or would regenerative fluxes based on dissolution such as that for silicic acid react differently than microbially mediated fluxes? Such questions are closely related to the evaluation of benthic coupling in the core module and share many of its logistical requirements.

In addition to the on-shelf regeneration of nutrients, horizontal exchange provides nutrients to the eastern shelf. Assuming steady state conditions, this horizontal exchange replaces the nutrients lost to the Bering Strait and sediment burial. However, the horizontal exchange of nutrients from the Aleutian Basin is poorly characterized. Clearly, shelf/slope exchanges will be affected by water movement onto and across the shelf, by mesoscale eddies, as well as by currents in the adjoining basin. Thus, this aspect of nutrient flux requires information on both local and regional physical processes. How closely is this supply linked to the large-scale atmospheric forcing that drives oceanic circulation and eddy formation in the Bering Sea? Does it respond strongly on similar seasonal, interannual, and decadal time scales? Ultimately, a better characterization of the individual nutrient supply mechanisms should enable an improved prediction of the year-to-year and longer-time-scale variations of shelf production, based on both local and remote physical forcing.

What local and remote physical ocean mechanisms, arising as a response to this variable forcing, control the magnitude and sources of nutrient replenishment on the shelf? What physical processes control the mechanisms, locations, and magnitudes of shelf/slope exchange? How do these variable forcings contribute to generating new production and establishing the consequent biological community structures over the shelf? How might these processes be expected to change under global warming scenarios?

Module 4: Post-bloom primary and secondary production and the role of summer stratification and warming

Recent observations show that the southeastern Bering Sea is warming and increasingly stratified during summer. Associated with this warming have been blooms of coccolithophores, observations of high densities of diatoms capable of forming harmful algal blooms, and an apparent decrease in important mesozooplankton such as the copepod *Calanus marshallae* and the euphausiid *Thysanoessa raschii.* Are these apparent changes new features of the southeastern shelf ecosystem, and are they spreading northward with the warming of the Bering Sea? What are the roles of warming and stratification in these changes? Are harmful algal blooms likely to become an important feature of summer post-spring-bloom production, and what are their implications for the safety of subsistence and commercial harvests?

Module 5: Regional studies at key locations for the exchange of heat, salt and nutrients to the eastern Bering Sea

Lateral control on the water mass characteristics of the Bering Sea is exerted by key straits and passes, as well as by important topographic and island features. Targeted studies of the influence of these features on the broad-scale productivity of the system are needed. Three regions of the eastern Bering Sea stand out as candidates for comparative regional studies. Each is a gateway that influences fluxes of heat and salts onto or way from the eastern Bering Sea shelf, and each is the location of substantial communities of Alaskan Natives who are dependent on local marine resources for commercial and subsistence harvests. Intensive studies within these regions will answer both questions of climate-ecosystem coupling and address specific concerns of regarding subsistence resources.

Northern Bering Sea. Bering Strait provides an outlet for water and nutrients advected onto the northern Bering Sea shelf and for influxes of freshwater from the rivers of western Alaska. The proportion of shelf water relative to Anadyr water and outflow from Alaskan rivers may vary significantly, but this variation is not well known at present. Bering Straight may also play an important climatic role on a global scale, especially for freshwater budgets, since waters of Pacific origin (> 20% original Pacific Water) can be traced as far south as the southern tip of Greenland. Thus, localized oceanographic changes in the Bering Sea can propagate to the Chukchi Sea and beyond, influencing a much wider geographical area. Within the northern Bering, changes in flow through Bering Strait may affect the advection of nutrients into the region, water temperatures, and sea ice cover.

Spatial patterns of primary productivity on the eastern Bering Sea shelf are also affected by upwelling at the shelf break and advection of those nutrients onto and across the shelf. In contrast to much of the central and southern shelf, where cross-shelf flows are relatively weak, episodic, and diffuse, the physics and biology of the northern portion (e.g., Chirikov Basin) are strongly influenced by the continuous, well-defined cross-shelf advection of the Anadyr Current. Consequently, interactions of wind, sea ice, algal blooms, and carbon flows to pelagic and benthic food webs may differ appreciably between the sluggish southern and central shelf vs. the highly advective northern shelf. The impacts on upper trophic consumers (fish, birds, mammals, humans) might include changes in ocean productivity, species' range shifts, and the northward migration of fisheries. Socioeconomic impacts will likely be related to enhanced shipping through the Bering Strait, increased fishing activities, impacts on Alaska Native communities via increased tourism and commerce, and impacts on subsistence hunting and traditional modes of travel. On the northern shelf, Yup'ik communities depend economically and culturally on harvest of marine mammals, supported by pelagic (bowhead whale) and benthic (walrus, bearded seal) food webs. In turn, these food webs depend on the interaction between ice cover and the strength of currents. Moreover, ice patterns affect not only the nature and productivity of local food webs in this region, but also the accessibility of marine mammals and humans to their food resources. A regional study of the northern Bering and southern Chukchi Seas might focus on the oceanographic processes, ecosystem functioning, and the potential impact of regional warming on sea ice cover, flow rates through Bering Strait, the ecosystem responses to these changes, and their socioeconomic impacts on local communities.

Communities of Yup'ik and Iñupiat people live on St. Lawrence Island, King Island (summer only), the Diomedes, and along the mainland coast and rely greatly on subsistence hunting and fishing. Many of these groups depend on hunting seasonally from fast ice, in leads and polynyas, as well as on transportation over the ice for hunting and movement between communities. How will climate change affect this highly advective system? If flows through Bering Strait change, what will be the affect on the relative amount of shelf and Anadyr water transiting the region? How are these changes linked to the ecosystems of the region? How will changes in freshwater flows affect the marine ecosystem? If water temperatures rise, what will be the effect on the distribution and abundance of species? How will these changes in bottom up forcing affect the local abundance and distribution of living marine resources, and what are the sociological and economic impacts on the local communities?

Pribilof Islands. The Pribilof Islands and the surrounding topographic features are in the middle of the "Green Belt" of elevated production. These islands and their surrounding waters support extensive populations of birds and marine mammals and some of the most productive fishing grounds of the eastern Bering Sea. They also support two large Aleut communities that depend directly or indirectly on the productivity of local waters for their economic well being. The elevated production can be traced to vigorous mesoscale activity associated with shelf-slope exchange. The mechanisms linking currents, meanders, eddies, and upwelling along the continental shelf slope and their impacts on nutrient replenishment in slope and shelf waters, however, need to be determined. A regional study might focus on the mechanisms responsible for enhanced localized productivity in this region, the roles of advection and retention for localized physical-biological coupling, and the implications of these mechanisms for upper trophic consumers (fish, birds, mammals, humans).

There are thriving Aleut communities on both St. Paul and St. George Islands that depend on local waters for commercial and subsistence harvests. What is the relative importance of this region for on-shelf fluxes of nutrients and plankton? What physical mechanisms are linked most closely to the maintenance of the shelf ecosystem? How do variations in slope-shelf fluxes influence the distribution and abundance of higher trophic level organisms? How will these changes in bottom-up forcing affect the local abundance and distribution of living marine resources, and what are the sociological and economic impacts on the resident and non-resident communities in this region?

Aleutian Passes. The Aleutian passes control lateral exchanges with the North Pacific Ocean. The factors controlling net northward transport through the Aleutian passes, however, need to be determined if we are to link changes in nutrient availability and transport in the Bering Sea to climate events at lower latitudes. In addition, we need to learn the mechanisms whereby the flow through Aleutian passes influences southeastern Bering Sea ecosystems. There appears to be a division in the characteristics of the water flowing through the Aleutian Passes, with the Alaskan Stream water flowing through the deeper western passes, and Alaska Coastal Current (ACC) water flowing through the shallow eastern passes. The ACC introduces heat and zooplankton to the southeastern Bering. Since maximum northward flow through Unimak Pass is in the winter, heat from this inflow may also play a role in limiting the maximum extent of ice along the Alaskan Peninsula. Net transport through the passes varies on many scales, including a strong fortnightly component in the deeper passes. Mesoscale eddies (in the order of 200 km across) are common along the Aleutian slopes. Flow through the passes provides a forcing mechanism for water mass modification in the southern Bering Sea at seasonal to interannual time scales, but their effects on ice extent and nutrient levels in the eastern Bering ecosystem have yet to be determined.

A regional study of the role of flow in the Aleutian Passes might address the major drivers of transport through the Aleutian Island passes, and the influence of these fluxes on the heat content, salinity, nutrients and zooplankton of the eastern Bering Sea shelf. Moreover, many higher trophic predators (fish, birds, mammals) forage in the vicinity of these productive passes, or move through during seasonal migrations between breeding and foraging grounds. Resident marine mammals (killer whales, sea lions, and seals) and humans take advantage of these resources, connecting these populations with broader regions of the sub-arctic North Pacific. The ecological and socioeconomic implications of this connectivity need to be understood to predict how human subsistence and commercial harvest economies will be impacted by physical and biological changes at local, regional, and basin-wide scales.

Large communities of Aleuts on Unimak, Akutan, Unalaska, Umnak, and Adak Islands and on the adjacent Lower Alaska Peninsula depend on local waters for commercial and subsistence harvests. How do flows through the passes affect the local availability of commercial and subsistence resources? How do flows in the passes react to changes in regional forcing mechanisms? How do variations in flows through the passes affect processes that influence on-shelf fluxes of nutrients and organisms? What are the temporal relationships between events in the passes, and the events that influence on-shelf fluxes of nutrients? How will these changes in bottom-up forcing affect the local abundance and distribution of living marine resources, and what are the sociological and economic impacts on resident and non-resident communities in the region?

Appendix 2. Glossary of BEST terms and acronyms

ARCUS: A non-profit corporation consisting of institutions organized and operated for educational, professional, and scientific purposes, established in 1988 to bring together the resources for Arctic research. www.arcus.org

Dimensions: The BEST Program envisions three intertwined disciplinary components: Physical Science, Natural Science, and Social Science.

ISHTAR: Study of the Yukon outflow on benthic processes in the northern Bering and Chukchi Seas, funded by NSF (1983–1991).

Inner-front study: NSF-supported study of the inner shelf front (40 m isobath) of the SE Bering Sea as a site of enhanced productivity and upper trophic predator aggregation (1997–2001)

GHG: Greenhouse Gases

International Polar Year (IPY): A major international science initiative involving an intense period (March 2007 to March 2009) of interdisciplinary research and data collection to provide a snapshot in time of the state of the Polar Regions. The first International Polar Year dates back to 1882–83. The 1957–58 International Geophysical Year, involving 80,000 scientists from 67 countries, was the last initiative of this kind. www.ipy.org

Modules: Prioritized set of broad research questions for the BEST program.

NPCREP: NOAA Climate and Ecosystems supported study, entitled North Pacific Climate Regimes and Ecosystem Productivity (2004–)

PROBES: Cross-shelf study of the southeastern Bering Sea, entitled Processes and Resources of the Bering Shelf, funded by NSF (1974–1982).

SEBSCC: NOAA Coastal Ocean Program supported study, entitled South East Bering Sea Carrying Capacity (1996-2002)

SSC: Science Steering Committee (see Appendix 3 for membership).

Appendix 3. Membership of the Bering Ecosystem Study (BEST) Science Steering Committee (SSC)

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