NPRB Proposal Summary Page

NPRB Use Only

Reference No: 56 **Date Submitted:** December 5, 2005
Date Received: December 6, 2005

(To be filled in by applicant)

Project Title: Modeling transport and survival of larval crab: Investigating the contraction and variability in snow crab stocks in the Eastern Bering Sea using Individual-Based Models

Project Period: From July 2006 To February 2009

Name, Address, Telephone Number and Email Address of Applicant:

Dr. Sarah Hinckley
Alaska Fisheries Science Center, NOAA
7600 Sand Point Way NE , Seattle, Washington, 98115, United States
206 526 4109
206 526 6723
Sarah.Hinckley@noaa.gov

Principal Investigator(s): (Include name, affiliation and email address):

Dr. Jeff Napp , Alaska Fisheries Science Center, jeff.napp@noaa.gov
Dr. David A. Armstrong , University of Washington, davearm@u.washington.edu
Dr. Albert J. Hermann , University of Washington, albert.j.hermann@noaa.gov
Dr. Carolina E Parada , Alaska Fisheries Science Center, NOAA, carolina.parada@noaa.gov
Dr. Billy Ernst , University of Concepcion, biernst@udec.cl, biernst@u.washington.edu
Dr. Bernard A. Megrey , Alaska Fisheries Science Center, NOAA, Bern.Megrey@noaa.gov
Dr. Jeffrey M. Napp , Alaska Fisheries Science Center, NOAA, jeff.napp@noaa.gov
Dr. Sarah Hinckley , Alaska Fisheries Science Center, NOAA, Sarah.Hinckley@noaa.gov
Dr. Gordon Kruse , University of Alaska/Fairbanks, gordon.kruse@uaf.edu
Dr. Jose Maria (Lobo) Orensanz , Centro Nacional Patagonico (CENPAT), lobo@cenpat.edu.ar; lobo@u.washington.edu
Dr. Al Hermann , University of Washington, hermann@pmel.noaa.gov

Research Priority and Subcategory:

Primary **2.d.iii** Life history, ecology and fluctuations in BSAI crab stocks
Secondary **1** Bering Sea Integrated Ecosystem Research Program

Summary of Proposed Work (250 words or less):
We will use an Individual-Based Model of larval snow crab coupled to an existing hydrodynamic model and a food model, along with data on distribution of crab larvae in the eastern Bering Sea. We will use these coupled models to investigate the spatial stock structure of female crab and its relationship to transport of larval stages, and the coupling of the ice-edge phytoplankton bloom and larval and early settler survival. We will also compare the model to data and design an optimal sampling strategy for larval snow crab using models and data. Three hypotheses are addressed: H1. Predominant currents and present spawning distributions of female snow crabs prevent transport of larvae to historical settlement areas in the Southeast Bering Sea); this process maintains the northerly distribution of snow crab females; H2. The timing, intensity and location of the ice-edge bloom affect survival of crab larvae in the Bering Sea; H3. Despite the contraction in range and decline in abundance of the spawning female population there have been some strong recruitment years based on a combination of a) change or reversal in prevailing northwesterly shelf-break currents to a more southeasterly direction, b) expansion of the summer cold pool which benefits post-settlement survival and, c) relaxation of cod predation on early settlement juvenile crab due to lower cod biomass in those years or less overlap with settling juveniles. We will perform five activities to investigate these hypotheses. These activities will yield information useful for management purposes.

Funding:

Total NPRB Funding Requested: **$296,746.00**
By Institution:
$171,327.00 (School of Aquatic and Fisheries Science,

NPRB Proposal Summary Page

	University of Washington) $125,419.00 (Alaska Fisheries Science Center, NOAA)
Total Matching Funds Used:	**$123,970.00** By Institution: $88,755.00 (Alaska Fisheries Science Center, NOAA) $35,215.00 (School of Aquatic and Fisheries Science, University of Washington)
Legally Binding Authorizing Signature and Affiliation:	

<u>**RESEARCH PLAN**</u>

***A. Project Title*:** Modeling transport and survival of larval crab: Investigating the contraction and variability in snow crab stocks in the Eastern Bering Sea using Individual-Based Models

***Short Title**:* Larval snow crab transport and survival in the Bering Sea

B. Proposal Summary: **(max 250 words).**

We will use an Individual-Based Model (IBM) of larval snow crab (*Chionoecetes opilio*) coupled to an existing 3D hydrodynamic model and a food model, along with data on distribution of crab larvae in the eastern Bering Sea. We will use these coupled models to investigate the spatial stock structure of female crab and its relationship to transport of larval stages, and the coupling of the ice-edge phytoplankton bloom and larval and early settler survival. We will also compare the model to data and design an optimal sampling strategy for larval snow crab using models and data. Three hypotheses are addressed*: H1. Predominant currents and present spawning distributions of female snow crabs prevent transport of larvae to historical settlement areas in the Southeast Bering Sea (SEBS); this process maintains the northerly distribution of snow crab females; H2. The timing, intensity and location of the ice-edge bloom affect survival of crab larvae in the Bering Sea; H3. Despite the contraction in range and decline in abundance of the spawning female population there have been some strong recruitment years based on a combination of a) change or reversal in prevailing northwesterly shelf-break currents to a more southeasterly direction, b) expansion of the summer cold pool which benefits post-settlement survival and, c) relaxation of cod predation on early settlement juvenile crab due to lower cod biomass in those years or less overlap with settling juveniles.* We will perform five activities to investigate these hypotheses. These activities will yield information useful for management purposes.

C. Project Responsiveness to NPRB Research Priorities or identified project needs

This project will result in increased understanding of the dynamics of snow crab recruitment processes and stock structure, and the response of this species to climate change, especially with respect to sea ice. It will also provide indices related to recruitment success to managers of this stock, and guidance to future field work. The primary NPRB research priority addressed is Number 2 (General Research Priorities on Ecosystem Components), Subcategory D (Fish and Invertebrates), Part iii (Life history, ecology and fluctuations in BSAI crab stocks). The second priority addressed is Number 1. Bering Sea Integrated Ecosystem Research Program “Response of the Bering Sea Ecosystem to Climate Change, Research Question a. “Are the distributions (range, spawning and breeding locations) and abundances of species in the Bering Sea ecosystem changing in response to climate change? If so, how?” Also addressed is Number 2 (General Research Priorities on Ecosystem Components), Subcategory B (Lower Trophic Level Productivity). The proposal addresses these priorities by using a set of coupled models to aid our understanding of how the present contraction of female snow crabs to the northern part of the Bering Sea affects (via larval transport) their potential to re-colonize historical spawning grounds in the SEBS. The proposal also addresses how the change in location of the ice-edge due to climate change may affect the survival of larval snow crab. We will also study the causes of high recruitment years. We will develop two indices related to snow crab pre-recruitment: a larval transport index, and an index of larval survival. This will aid managers in understanding recruitment processes, present and future stock structure of snow crab, and their response to climate change. This project will provide guidance for efficient use of resources in future field-work on snow crab. Another benefit of this project will be to link parties interested in management and research of snow crab (Alaska Department of Fish and Game (ADF&G), National Marine Fisheries Services (NMFS) NOAA, University of Washington (UW), University of Alaska Fairbanks (UAF)).

D. Project Design and Conceptual Approach

The present state of the knowledge in the field: Snow crabs form one of the most important and fluctuating fisheries in the Bering Sea. Substantial reductions in abundance, and spatial contraction of the snow crab stock has been observed in the eastern Bering Sea (EBS), and the recommended catch level has reached an historical minimum in several recent years (Rugolo et al., 2003). Over the last three decades the geographic range of distribution of snow crab has contracted dramatically to the north of its former geographical range (Orensanz et al., 2005). Snow crab annual recruitment in the EBS has fluctuated between high and low periods, with the resultant recruitment of large males reaching dramatic and historical low levels in 1994 and 2001 (Fig.1,Rugolo et al., 2003). Documented changes in abundance have been accompanied by changes in spatial structure of the stock (Orensanz et al., 2005), this is also true of other crab species (Armstrong et al., 1993; Loher and Armstrong 2005).

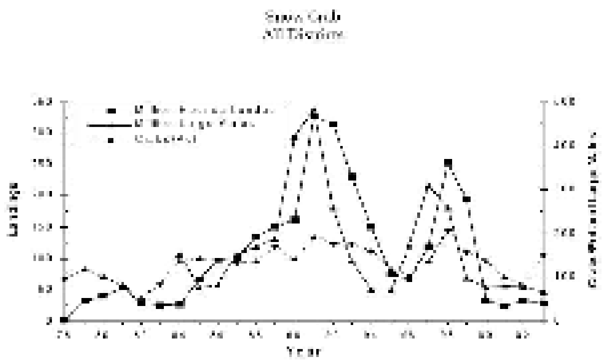

Fig.1. US Landings in millions of pounds, CPUE as crabs /pot-lift, and the abundances of large male snow crab (*C. opilio*) millions (all districts combined), estimated from NMFS trawl surveys (Rugolo et al., 2003)

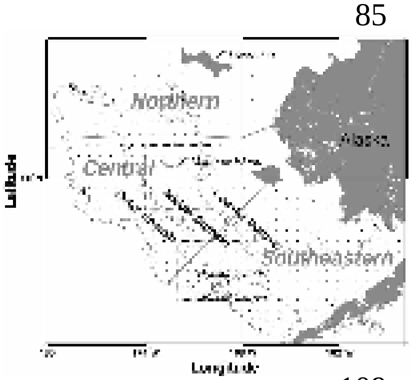

Fig. 2 The Eastern Bering Sea (EBS). Dots indicate NMFS survey stations where snow crab was observed at least once during surveys conducted between 1975-2001. Dashed rectangles around the Pribilof Islands and St. Matthew Island that were defined to study the relationship between ontongenetic changes in crab and environmental variables in Orensanz et al., 2004.

It has been hypothesized that declines in crab abundance, which have coincided with shifts in the spatial distribution of females, could have altered larval production and transport patterns (Loher and Armstrong, 2005). Unfavorable transport of larval crab has been proposed as one explanation affecting recruitment to the SEBS, but a quantitative analysis of this hypothesis is lacking. In the case of snow crab, the change in spatial structure of the female part of the population has been a marked northward contraction of the southern edge of the distribution. The main distribution of spawning females is now in the northern Bering Sea, and the predominant currents flow from southeast to northwest. This would prevent southward advection of hatching larvae. Given our knowledge of the prevailing currents (Coachman 1986; Schumacher and Stabeno, 1998), it would appear impossible for larvae to “repopulate” the southern part of the outer and middle domains of SEBS (Fig. 2). This would prevent the expansion of the population back to its historical distribution (Orensanz et al., 2005). Likewise, there is evidence in other crab species (i.e. red king crab) that changes in the transport and distribution patterns of pre-settlement larvae have important consequences to differential recruitment contributions in different regions (Hsu, 1987; Armstrong et al., 1993).

Variability in larval snow crab survival may have been affected by changes in the timing and location of the ice-edge bloom. Snow crab larval survival is thought to be associated with the ice-edge phytoplankton bloom (Somerton, 1981). The mean ice extent and other ice properties have been changing in the Bering Sea (Overland and Stabeno, 2004). There is a clear overall downward trend in the ice retreat index (IRI, representing the number of days with ice cover after March 15). Since the early 1970s, the IRI has declined an average of 1 day per year (Rodionov et al., 2005, NOAA Rep. on the EBS. http://www.beringclimate.noaa.gov/reports/bs_05.pdf).

The presence of ice is directly related to the timing of the spring primary production bloom in those areas where the ice is present (Stabeno et al., 1998, Hunt et al., 2002). Late ice retreat leads to an early (late March or early April) ice associated bloom in cold water (Hunt et al., 2002). Since crab larval abundance is observed to peak in April, the larvae are more likely to have faster growth and better survival in cold years when the ice-edge bloom coincides temporally and spatially with larval release. The relationships between the dynamics of larval transport, variability in larval crab survival, and ice edge blooms are not well understood. Recruitment trends for some crab stocks are partially related to decadal shifts in climate and physical oceanography (Zheng and Kruse, 2000). Inter-annual variability in physical variables and oceanographic processes have the potential to affect the transport patterns of early life stages of crabs in the EBS, as well as the survival of crab larvae due to fluctuations of the spring bloom of phytoplankton and its effect on production of zooplankton prey items (Paul and Paul, 1980; Paul et al. 1989; Incze and Paul, 1983).

Attempts have been made to relate the dynamics of crab populations with environmental factors based on aggregated statistics such as time series of recruitment indices (Zheng and Kruse, 2000). Incze et al. (1987) computed mixed layer depth in the SEBS and used quantitative data on larval snow and tanner crab vertical distribution and abundance to study correspondence with benthic female distribution and food supply. No circulation model was available to analyze advection patterns. In the EBS modeling efforts were conducted to simulate red king crab larval advection using a 2-layered box model representing the Bristol Bay region (Loher, 2001). In recent years, physical circulation models have improved substantially for the EBS. The Regional Ocean Model System (ROMs, Haidvogel et al., 2000) has now been adapted to the EBS system, and includes relevant physical features such as ice and tides. This recent improvement is considered an excellent opportunity to study the dynamics of crab populations with environmental factors in a realistic manner.

The snow crab fishery is economically important in the EBS. The current level of knowledge of the spatially-explicit reproductive potential of snow crab and the present availability of appropriate physical models, makes it timely to study the effects of oceanographic circulation on the early life history dynamics of crab using a mechanistic approach. The use of a high resolution hydrodynamic model to simulate current patterns in the EBS coupled to a mechanistic IBM of crab larvae is a necessary step towards studying transport of crab larvae and exploring environmental effects on these stocks.

Some of the relevant questions are: (1) is the northward female snow crab contraction affecting the re-colonization of the population back to its historical domain in the SEBS via larval transport processes? (2) How is this process related to patterns in climate change, and are trends in ice retreat in EBS influencing the location and timing of the spring ice-edge bloom thereby affecting the survival of snow crab larvae? (3) In years where there was good recruitment of snow crab, (a) were there reversals in currents that would transport larvae farther to the southeast, (b) were bottom temperatures colder in those years (positively affecting settlers which prefer cold temperatures), and (c) was the cod biomass low or not overlapping with early settlement juveniles in those years?

The main objective of this research is to study the effects of transport and survival of snow crab larvae by using an IBM coupled to a hydrodynamic model and an NP (nitrogen-phytoplankton) model, along with biological information on crabs in the EBS. We will collect data on larval crab in 2006 and use this to estimate parameters of the larval crab IBM, use model experiments to design optimal plankton survey strategies, and extract indices from the IBM related to stock structure and recruitment to give preliminary advice to managers of the snow crab fisheries (ADF&G and NMFS).

Projects relation to previous work:

This proposal is not intended as an extension of a previously funded NPRB project, however, it does build upon previous NPRB grants to these PIs. This project is linked directly to the research on contraction of snow crab female populations in EBS, as conceptualized in the "Environmental Ratchet" hypothesis (Orensanz et al., 2004). They observed that the geographic range of the mature female snow crab population has contracted from southeast to northwest (Fig. 3). During the 5-year period between 1978 and 1982, the mature population was spread over the entire EBS shelf, with large concentrations in the southeast (near the Pribilof Islands) and the northwest (near St. Matthew Island). In contrast, during the 5-year period 1998–2001, the southeast concentration disappeared, and nearly all the mature population was concentrated north of 58°N (Fig. 3). Between these two periods there were some transient expansions of the mature female stock. Contraction to the north was accompanied by a long-term decline in abundance, punctuated by periodic good pseudocohort recruitment in 1980, 1987, 1994, and 2001.

These good years may be explained by: (1) a reversal in predominant currents in those years, (2) colder temperatures in the SEBS favoring early stage juveniles, or (3) a reduction in cod predation on juveniles due to lower cod biomasses or less overlap of cod and juvenile crabs. Orensanz et al. (2004) have hypothesized that the contraction of the population will make repopulation of the SEBS by crab larvae unlikely.

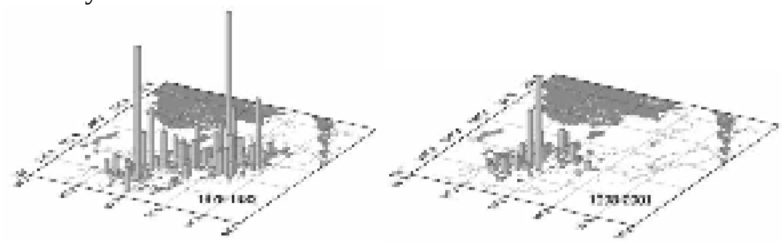

Fig.3 Aggregated abundance of primiparous females at the beginning (left 1978-1982) and toward the end (right, 1998-2001) of the study period. Bar height is proportional to abundance (survey CPUE) in each cell, aggregated for the period indicated (Orensanz et al., 2004).

This larval transport and survival project builds on five other research projects (past and present):
(1) This project will be tightly coupled to a current NPRB project entitled "Female Effective Reproductive Output (FERO, NPRB 508) of snow crab stocks in the eastern Bering Sea: how much, why, and implications for management." by Armstrong et al., (2005). Researchers in this study are examining how biophysical factors affect adult female crab and control of the present distribution by predation on juveniles by cod. We will be using a model to examine biophysical effects on larval crab. This will complement the work on adults by examining transport and survival processes of the earlier life stages and how this affects settlement areas, therefore potential thermal effects and settlers and overlap with cod. FERO will provide an important base for the biological structure needed to model larval transport and survival processes by providing spatially-explicit estimates of egg and larval production based on mature female distribution and abundance over a 29 year period (1975-2004). Results will help guide parameter estimates and initial conditions for various scenarios explored in model runs for this proposal. Spatially-explicit female data including abundance by shell condition index, size, and relative fecundity (including biennial spawning) will make more accurate the spatial origin of larval "swarms" released into various advection runs to determine patterns of advection and location at settlement by end of larval ontogeny.
(2) The FY2005 FATE (Fisheries And The Environment) project of Hermann et al., (PMEL (Pacific Marine Environmental Laboratory), NOAA) "Continuation of multi-decadal simulations of circulation and walleye pollock in the Northern Gulf of Alaska" based on the use of ROMS circulation model that includes the EBS, has funded some of the runs of ROMS and an NP model in the Gulf of Alaska (GOA) and Bering Sea. (3) The NPRB project (No. 523) "Pollock recruitment and stock structure" by Hinckley et al. which uses the same techniques of coupling hydrodynamic models to IBMs to study recruitment dynamics, transport, and survival of early life stages of walleye pollock in the GOA. The goal of this project is also to advise managers and develop indices useful in management. (4) NOAA's North Pacific Climate Regimes and Ecosystem Productivity (NPCREP) program, that is investigating how changes in climate affect the structure and function of marine ecosystems in the Gulf of Alaska and Bering Sea. (5) The GLOBEC (Global Ecosystems) project of Hermann et al. entitled "Coupled biophysical models of the GOA (2000). Under this support, we constructed a model that simulates currents using a ~10 km resolution for the Northeast Pacific (NEP) and the Bering Sea over the full period 1947-present.

The circulation modeling, which is used by the present proposal, is based on the Regional Ocean Modeling System (ROMS). ROMS is a state-of-the-art, free-surface, hydrostatic primitive equation ocean circulation model developed at Rutgers University and UCLA. Numerical details can be found in Haidvogel et al. (2000), Moore et al. (2004) and Shchepetkin and McWilliams (2005), and on the ROMS web site (http://marine.rutgers.edu/po/index.php?model=roms). ROMS capabilities include Lagrangian tracking of passive floats, and Eulerian advection and mixing of user-defined tracer distributions. Drifter tracking in ROMS is accomplished using a fourth-order predictor-corrector scheme and allows vertical movement (ie. diel or ontogenetic migrations of larvae). This float tracking capability has been successfully applied for a variety of fisheries applications, and results compared with drifter data

(Hermann et al, 2002a; Hermann et al, 2002b; Stabeno et al., 2004). In particular, we have used the NEP model to simulate trajectories at fixed depths in the southeastern Bering Sea during 1997-2001 (see Fig. 4). These particles were tracked for 90 days, with resultant transport to both the northwest and the northeast simulating transport of northern rock sole, *Lepidopsetta polyxystra* (Lanksbury et al. in prep). It is interesting to note that few of the trajectories reversed direction, indicating that the major direction of transport in this region is to the north. This may support the idea that the present snow crab spawning in the northern Bering Sea is downstream of the historical grounds, and that return to these grounds by passive transport of larvae is unlikely, however drifters in this study were released only in Unimak Pass. We need to extend the area and times of float release for this study.

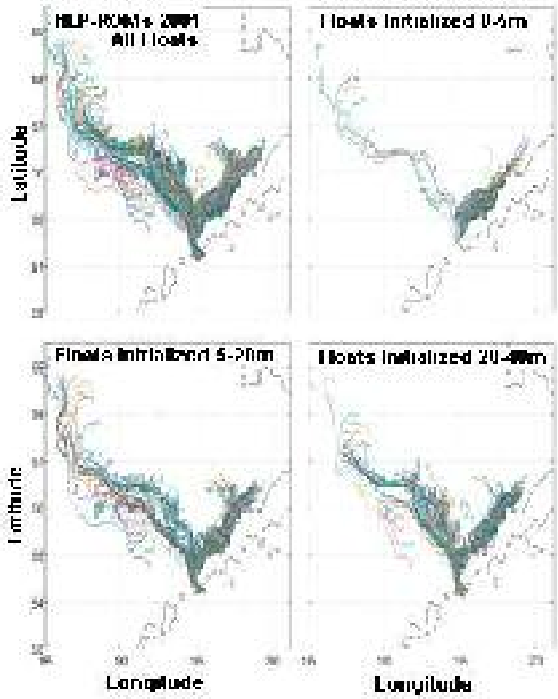

Fig.4. Simulated 90-day drifter tracks for 2001 in the Southeast Bering Sea, as a function of release depth in Unimak Pass.

This study builds on previous studies which used the Semispectral Primitive Equation Model (SPEM; Haidvogel et al, 1991) for passive float tracking (Hermann and Stabeno, 1996; Hermann et al., 1996a) and a spatially explicit IBM of walleye pollock eggs and larvae, which include vertical migrations according to life stage (Hinckley et al, 1996; Hermann et al, 1996b; Hermann et al., 2001, Parada et al. In prep.a). The use of NEP-ROMS proposed for this project constitutes a significant advance over the use of SPEM.

Measurable benefits from proposed research:

This research will provide managers of crab stocks with information on causes of recruitment variability at annual and decadal scales. We will also provide pre-recruit indices (based on crab larval survival and transport) useful for **forecasting** the size of pseudocohorts before they enter the fishery and information about stock structure. The research will improve our ability to manage this important resource, and assess effects of climatic shifts on the stocks. Insight into snow crab stock structure, spatial distribution and recruitment related to climate shifts will also aid in understanding of the effect of these shifts on the ecosystem of the Bering Sea. In comparison to other snow crab stocks (e.g. Atlantic Canada) little is known about temporal and spatial dynamics of larval, early benthic and juvenile stages of snow crab in the EBS. This project will build a conceptual framework for early life history dynamics and will provide a quantitative tool to design surveys for snow crab larvae. Sampling early stages of snow crab was encouraged in the 2005 NPRB call for proposals.

Conceptual or statistical model underlying experimental work:

This research involves the exploration of the interaction of physical and biological mechanisms of transport and survival of crab larvae in a climatic change framework in the EBS via coupled biophysical model techniques. The coupled biophysical model consists of : (1) output of the ROMS model, (2) a simple Nitrogen-Phytoplankton (NP) model (as a module of ROMs), and (3) a spatially-explicit IBM of the crab early life history. The hydrodynamic model output will provide with environmental variables such as 3D velocity, salinity and temperature fields. In particular, our implementation of ROMS includes a free surface, advanced vertical mixing algorithms, superior numerics for horizontal advection, and more accurate vertical resolution of the flow field. The version of ROMS we will use in this study also includes ice. These features will yield more accurate spatial paths of tracked floats, plus the ability to simulate ice-edge blooms. The NP model module of ROMs will be run to produce an estimate of timing and location of ice-edge blooms. This model will provide with a coarse food index to study the co-occurrence on time and location of ice-edge bloom with the crab larvae to estimate an index of larval crab survival. The IBM for crab larvae will represent the trajectory of crab larvae through the advection and diffusion of simulated drifters with behaviors. The IBM will follow individuals from release into the water column, to the end of the pelagic larval stage just before settlement. The incorporation of biology, including simple functional relationships between growth, mortality and temperature, and vertical migration strategies, will be modeled. From the coupling of the ROMs outputs and IBM for crab larvae we will extract a transport index that account for the repopulation of crab larvae to the SEBS.

The advantage of this approach is the inclusion of explicit biological and physical mechanisms. Other research projects have approached the study of timing and location of spawning areas of early stages of fishes using IBMs (Hinckley et al., 1996; Hinckley, 1999; Hermann et al., 2001; Huggett et al., 2002; Parada et al., 2003, Parada et al., In prep. b); others, have looked at the effect of physical features such as turbulence, eddies and advection (Hermann and Stabeno, 1996; Megrey and Hinckley, 2001) on larval fish. Some recent work has attempted to estimate pre-recruitment indices and relate them with biophysical variables using a coupled biophysical model (Parada et al., In prep b). We intend to use coupled models to test a series of hypotheses related to transport and survival of snow crab in EBS.

Hypothesis, experimental design and analytical approach: Three hypotheses are addressed in this project:
H1- Predominant currents and present spawning distributions of female snow crabs prevent transport of larvae to settlement areas in the Southeast Bering Sea; this process maintains the northerly distribution of snow crab females.
H2 - The timing, intensity, and location of the ice-edge bloom affect survival of crab larvae in the Eastern Bering Sea.
H3- Despite contraction in range and decline in abundance of the spawning female population, there have been some strong recruitment years leading to large abundances of primiparous females in 1980, 1987, 1994 and 2001. These result from a combination of: a) a reversal in prevailing northwesterly shelf-break currents to a more southeasterly direction, b) an expansion of the summer cold pool to benefit post-settlement survival and, c) a relaxation of cod predation on early settlement juvenile crab due to lower cod biomass in those years or less overlap with settling juveniles.

Five activities will be performed to address these hypotheses:
Activity 1: Estimate parameters of the IBM using data collected in 2006 (surveys conducted by the Eco-FOCI (Ecosystems and Fisheries Oceanography Coordinated Investigations) program of NOAA). In IBMs, parameters are often based on life history characteristics of the species, and bibliographic information on the species, genus or family, and on data. Sensitivity analyses are performed to assess the effect of these model assumptions on the results. However, the chosen parameter values are seldom based on formal statistical parameter estimation. We intend to perform a formal parameter estimation of selected parameters using a maximum likelihood approach. This is a novel exercise in this modeling area and the success of this effort will depend on computational efficiency and the adequacy of the data collected in the larval survey of 2006. Also, this activity is a necessary precursor to using the model to address hypotheses.

Activity 2: Assess the effect of initial locations of reproductive on the potential abundance and distribution of pre-recruits. Using ROMS velocity fields and the IBM model initialized with the locations and timing of release of larvae (from the FERO project), we will extract an annual index that accounts for the number of larvae that are transported to the SEBS. The activity will allow us to test Hypothesis 1.

Activity 3: Study the co-occurrence and effects of the ice-edge bloom on larval survival. We will use a simple NP model to study the co-occurrence on time and location of ice-edge bloom with the crab larvae. We will modify larval survival based on the biomass of phytoplankton that larvae encounter to estimate an index of larval crab survival. The survival index will be computed yearly and compared to the year-class strength. This activity is related to Hypothesis 2.

Activity 4: Assess mechanisms underlying high recruitment. We will examine the biophysical model output to see whether currents show a reversal of the predominant northwesterly currents to more southeasterly directions in high recruitment years. Secondly, we will examine the bottom temperatures at the locations of individuals at the end of the pelagic stage. Thirdly, we will examine the distribution of individuals at the end of the pelagic stage with the distribution of cod (from the FERO project). From these examinations, we will construct an index of the potential for successful settled juvenile success. This activity is related to Hypothesis 3.

Activity 5: Use the IBM to design an optimal sampling strategy for snow crab larvae
Temporal and spatial information of snow crab larvae predicted by the IBM model will be used to assess timing and optimal sampling strategy for snow crab larval surveys. We will use basic statistics and model output for all years to analyze the spatial location, timing and inter-annual variability of snow crab larvae. These results will help to constraint the spatial and temporal coverage necessary for future surveys. Based on these results we will identify a range of scenarios over which we will test the efficiency of sampling estimators derived from alternative sampling designs (e.g. simple random sampling, stratified sampling, adaptive sampling). We will use a randomization algorithm to simulate the spatial distribution of the larvae for each scenario and use the relative error statistic to compare sampling design performance.

Outcomes: The expected outcomes of this proposal will be:

- An improved understanding of the relationship between the northward contraction and lack of re-colonization of the southern areas by female snow crabs.
- An improved understanding of the relationship between ice retreat, the timing and location of the ice-edge bloom, and the effect on survival of larval crab.
- An increased understanding of the interaction between transport processes and the survival of larvae related to ice-edge blooms, and how these are related to climate change.
- An improved understanding of recruitment mechanisms
- A time series of three pre-recruitment indices (transport, larval survival, probability of high juvenile survival) based on the output from the model, compared to actual snow crab recruitment. The strength of these correlations will indicated the usefulness of these indices.
- An optimal sampling design for snow crab larvae.
- An operational model system that could be used to predict year class strength several years ahead of actual recruitment to the fishery.
- The publication of peer-reviewed journal articles describing the results of this research
- Presentation of results at the annual Alaska Marine Science symposium

To fulfill the Outreach and Education requirement for this proposal, we will organize a workshop for managers of crab stocks and students in fisheries on this research and its results, and on possible operationalization of this model system.

E. Project Management

Dr. Hinckley will be responsible for overall project coordination and project reports to NPRB. She will advise on the design of the models, overall goals and methods and model experiments. She will work on tuning of the NP model and will coauthor papers. Dr. Hinckley is the originator of the biological models (IBM and NP) used in this work, and is Subtask Leader of the Ecological and Ecosystem Modeling Group in the Eco-FOCI program at the Alaska Fisheries Science Center. She has managed several other modeling projects on pollock recruitment, Steller sea lion foraging and behavior, and lower trophic level ecosystems dynamics of the Gulf of Alaska.

Dr. Parada will work on the design and implementation of the IBM and NP models, and model experimental design. She will be in charge of day-to-day programming, model runs, experiments and analysis of the results of the modeling. She has advised and trained students at the University of Concepcion, Chile on theoretical aspects and on the programming techniques for IBMs. She worked with IBMs of the Benguela ecosystem (for anchovy) that utilized the ROMS model. Dr. Parada has experience with the pollock IBM, with a NPZ model and with the ROMS model in the GOA, which includes work funded under NPRB Project 523. Results from Project 523 will be used in a management framework. She will actively participate writing manuscripts. Dr. Parada will work for six months in Year 1 and six months in Year 2 on this project. During Year 2, Dr. Parada will be working from South America and traveling to Seattle for at least 3 month to interact with the group.

Dr. Hermann will be chiefly responsible for the generation of velocity, temperature and ice fields, and advising on the coupling of physical with biological models. He will direct UW/JISAO (University of Washington Joint Institute for the Study of Atmosphere and Oceans) staff in these efforts. Dr. Hermann has been involved in physical oceanographic modeling in the Eco-FOCI program and the GLOBEC program. He has adapted several hydrodynamic models (SPEM, SCRUM [S-coordinate Rutgers University Model]), ROMS) to the North Pacific, and has aided in the work on the biological NPZ and pollock models. He has been a PI on GLOBEC NEP Biophysical Modeling projects, SEBSCC (SouthEast Bering Sea Carrying Capacity) physical and biophysical modeling projects, FATE biophysical modeling projects, the NPRB funded pollock recruitment modeling work (NPRB Project 523) and NOAA HPCC (High Performance Computing and Communications) projects.

Dr. Megrey will advise on issues relevant to management, forecasting, and model experimental design. Dr. Megrey has been involved with the IBM modeling work as the Modeling, Prediction and Databases Team Leader in the FOCI program at AFSC (Alaska Fisheries Science Center). He is presently involved in projects involving climate research and fisheries, GOA ecosystems monitoring, high performance computing and ecological forecasting.

Dr. Armstrong will provide general guidance, will coordinate the UW side of the project, and will act as an interface between this proposed research and the FERO project. He will advise on life history parameters for the larval crab IBM, and on the computation of meaningful year-class-strength statistics. He has 25 years experience in crab life history and ecology in the Bering Sea. Dr. Armstrong will provide about 2 full time months, however he will receive no direct funding from this proposal. He presently serves as Director of the School of Aquatic and Fisheries Science at the University of Washington.

Dr. Ernst will provide information on EBS snow crab effective female reproductive output over time and space (1978-2004) and advice on designing some of the experiments. He will help to setup the parameter estimation procedure and contribute in the assessment of optimal sampling design. Dr. Ernst has been involved in the analysis of survey and fisheries data of EBS snow crab since 2001. Most of the work has been related to modeling of the mature female stock (abundance, spatial distribution, migration, fecundity, computation of effective reproductive output, etc).

Dr. Orensanz will provide general guidance in the calculation of EBS snow crab effective female reproductive output and work on the conceptual design of the IBM. He will actively participate in writing manuscripts. Dr Orensanz has been involved in the analysis of survey and fisheries data of EBS snow crab since 1990. Most of the work has been related to modeling of the mature female stock (abundance, spatial distribution, migration, fecundity, computation of effective reproductive output, etc). Dr Orensanz has extensive experience on reproductive biology and population dynamics of crabs stocks.

Dr. Kruse will provide advice to the project based on his experience in crab population dynamics and fishery oceanography. He is the President's Professor of Fisheries at the School of Fisheries and Ocean Sciences, University of Alaska Fairbanks. Dr. Kruse will share insights on recruitment processes gathered during a workshop that he co-convened involving international experts on snow crabs, as well as his research on shifts in snow crab distributions in the eastern Bering Sea. He is currently proposing a complementary study on Tanner crab recruitment in the eastern Bering Sea and research into the decline of red king crabs off Kodiak. His participation fosters collaborations among all these projects.

Dr. Napp will be Chief Scientist on one of the 2006 spring cruises that collect crab larvae. He will be responsible for planning the coordinated sampling at and near the ice edge for snow crab larvae. He will work with the Polish Plankton Sorting and Identification Center and a taxonomic expert, Ms. Deborah Siefert, to accomplish identifications and discrimination of Snow crab larvae. He will work with the other PIs to interpret and incorporate the data into the model and will help evaluate the different optimal sampling strategies suggested by the ROMS-IBM-NP model. Dr. Napp has been working in the southeastern Bering Sea for the past 12 years to understand how climate and upper ocean physics influences the flow of energy from lower to upper trophic levels (fish, mammals, and birds). He was a Principal Investigator on several multi-disciplinary programs in the NE Pacific Ocean (FOCI, BS FOCI, SEBSCC, GLOBEC) and regularly publishes his results. He currently has one NPRB project (with P. Stabeno) to monitor the southeastern Bering Sea using moorings. He served as a Guest Editor for a special issue of Deep-Sea Research, dedicated to articles on the Bering Sea, and writes a semi-annual piece for the PICES Press on recent events in the Bering Sea. Dr. Napp also served on the NSF-sponsored committees that wrote the Bering Sea Ecosystem Study (BEST) Science and Implementation plans.

D. Righi (UW/JISAO staff) will be responsible for running the ROMS/NP model and for managing model outputs. The postdoc will be responsible for implementing model coding, running experiments, and performing analyses. The postdoc will work full time for 1.5 years. Ms. Deborah L.W. Siefert will verify the identifications of crab larval samples. She accomplished the original Bering Sea crab larvae identifications for L. Incze in the 1980s as part of PROBES.

Meetings of PIs and the postdoc will be held (via videoconferences, teleconferences, or in person) four times a year, to discuss project needs, personnel roles, and progress. Drs. Ernst and Orensanz will travel to Seattle once in 2007 for working visits of 1-2 months, and Drs. Ernst, Orensanz and Parada will travel to Seattle for a comparable interval in 2008. Dr. Kruse will travel to Seattle once in Year 1 (funded by another project), and once in Year 2 for consultations.

Coordination and Collaboration with other Projects

We will coordinate this research with several other ongoing projects at AFSC, PMEL, UW and UAF. Development of techniques for coupling biological models with the ROMS model, running the some of the appropriate years of the ROMS model (which includes both the GOA and the Bering Sea), and development of an IBM model template has resulted from ongoing work on the NPRB pollock recruitment modeling work (Project #523). PIs Armstrong, Ernst and Orensanz are also involved in the NPRB project No. 508. Planning for the current project has been done in close collaboration with the FERO team so that the combination of scientists now included form a comprehensive blend of crab biology and ecology, oceanographic and IBM modeling. Hermann et al.'s 2005 FATE proposal developed the Live Access Server methodology and will produce ROMs and NP model hindcasts which will be used by this project. The 2005 FATE proposal also funded aspects of the work on the pollock IBMs, which can be transferred to this project. Other currently funded modeling activities (under GLOBEC and related programs) include multi-decadal modeling of Bering Sea physical fields at 10-km resolution. Work proposed to the BEST program by Hermann and colleagues will include a fine-scale (3 km resolution) model of the Bering Sea, and formal assimilation of physical measurements (e.g. current meter data). Circulation/temperature hindcasts from both efforts will be used for the IBM research proposed here. The present proposed research will be coordinated with the proposed tanner crab research (Kruse et al.) These projects will share principal investigators and collaborators to assure efficiency of information exchange, cost-effectiveness (e.g., shared ocean model runs), and high-quality results benefiting from the combined expertise of the research team at UAF, PMEL, AFSC, UW, and ADF&G.

Milestones and schedule: (Start date July 1, 2006)

Year	**Product**	**Completion Date**
Year 1	Sample crab larvae on NOAA cruises	May 2006
	Complete conceptual model of crab larval IBM and tuning of NP model to produce ice-edge bloom	Oct 2006
	Complete collection of parameters and initial conditions for IBM	Jan 2007
	Complete identification of crab larvae	May 2007
	Complete development and programming of IBM and coupling with ROMS/NP	Jun 2007
Year 2	Complete Activity 1-5	Mar 2008
	Complete draft manuscripts	Jun 2008
	Present final results at Alaska Marine Science Meeting	Jan 2009

Products of This Proposal

The results of this research will be published in papers in peer-reviewed scientific journals. Also, we expect to develop pre-recruit indices for larval snow crab which can be generated via an operational model usable by fisheries managers. We will also provide an optimal sampling plan to scientists in FOCI (and elsewhere) who intend to survey for larval snow crab.

Responsibility for overall work/Binding Contracts

Dr. Hinckley will be the lead PI and responsible for ensuring that the work gets done in a thorough and timely manner. We envision two binding contracts, one with NOAA/AFSC, and one with UW School of Ocean and Fisheries Science.

Principal Investigator(s):

Dr. Sarah Hinckley (AFSC/NOAA, sarah.hinckley@noaa.gov)
Dr. David Armstrong (UW/SAFS (School of Fisheries and Aquatic Science), davearm@u.washington.edu)
Dr. Carolina Parada (UW/JISAO and AFSC/NOAA, carolina.parada@noaa.gov)
Dr. Jeffrey Napp (AFSC/NOAA, jeff.napp@noaa.gov)
Dr. Bernard Megrey (AFSC/NOAA, bern.megrey@noaa.gov)
Dr. Albert Hermann (UW/JISAO and PMEL/NOAA, albert.j.hermann@noaa.gov)
Dr. Lobo Orensanz (Centro National Patagonico, Argentina; Affiliate Faculty UW/SAFS, lobo@u.washington.edu)
Dr. Billy Ernst (U. Concepcion, Chile, biernst@u.washington.edu, biernst@udec.cl)
Dr. Gordon Kruse (U. Alaska Fairbanks, SFOS, Gordon.Kruse@uaf.edu)

F. Project Costs.

In the AFSC portion of this budget we ask for .75 mo/yr for two years for Dr. Hermann (JISAO/UW). We also ask for .75 mo/yr for two years for D. Righi (technician and computer support, JISAO/UW). Dr. Parada will be working six mo/yr for two years (JISAO/UW). Benefits for Hermann and Righi are charged at 27.1%, and for Parada, 23.2%. Travel funds are requested for Parada to attend the Alaska Marine Sciences conference in Anchorage in Year 2 and the year following the project end date (included under Year 2) at $1500 per trip. Travel funds are also requested for Parada to come to Seattle from South America in Year 2 ($1500, per diem will not be charged for this trip), and for Gordon Kruse to come to Seattle from Juneau in Year 2 ($1500). We intend to purchase a RAID array (hard disk) for storing model output, a dual boot laptop computer for Parada, and a desktop computer for the postdoc. We ask for $2,500 for publication costs in Year 2. In Year 1 we will contract a technician to sort larval crab samples ($5200). We have included $1,000 in each year for education and outreach. A fee of .5% is charged by PMEL to transfer money from AFSC to JISAO/UW, this totals $194 in each year, and is placed in the "Other" category. JISAO/UW charges overhead (indirect costs) at the rate of 26% on salaries and benefits for Hermann, Righi and Parada.

NOAA will pay salaries and benefits for Hinckley (2 mo/yr), Megrey (2 wk/yr), Napp (2 wk/yr), and C. Harpold (1 mo/yr).These are included in Matching Funds from AFSC. Small sums for lab supplies and postage will be included in Matching Funds from AFSC.

In the UW/SAFS, we ask for one month of salary for Dr. Orensanz in Year 1 and two months salary in Year 2. We ask for one month of salary for Dr. Ernst in Year 1 and 3 months in Year 2. The postdoc will work a full year in Year 1 and six months in Year 2. The benefit rate for Orensanz and Ernst is 11.1%, and for the postdoc is 23.2%. Travel funds are requested for Orensanz and Ernst for Year 2 at $1500 each to come to Seattle from South America. The overhead rate for UW/SAFS is 26%. Dr. Armstrong will work 2 mo/yr; his salary is included as Matching Funds from UW/SAFS.

References

Armstrong, D.A., Wainwright, T.C., Jensen, G.C., Dinnel, P.A. and H. B. Andersen. 1993.. Taking refuge from bycatch issues: Red king crab (*Paralithodes camtschaticus*) and trawl fisheries in the Eastern Bering Sea. Can, J. Fish. Aquat. Sci. 50: 1993-2000.

Coachman, L.K. 1986. Circulation, water masses, and fluxes on the southeastern Bering Sea shelf. Cont. Shelf Res. 5: 23-108.Haidvogel, D. B., Wilkin, J. L. and R. Young. 1991. A semi-spectral primitive equation ocean circulation model using vertical sigma and orthogonal curvilinear horizontal coordinates. J. Comput. Phys. 94: 151-185.

Haidvogel, D.B., Arango, H.G., Hedstrom, K., Beckmann, A., Malanotte-Rizzoli, .P., and A.F. Shchepetkin. 2000. Model Evaluation Experiments in the North Atlantic Basin: Simulations in Nonlinear Terrain-Following Coordinates. Dynamics of Atmospheres and Oceans. 32: 239-281

Hermann, A. J. and P. J. Stabeno. 1996. An eddy resolving model of circulation on the western Gulf of Alaska shelf. I. Model development and sensitivity analyses. J. Geophys. Res. 101: 1129-1149.

Hermann, A. J., Rugen, W. C., Stabeno, P. J. and N. A. Bond. 1996a. Physical transport of young walleye pollock larvae (*Theragra chalcogramm*a) near Shelikof Strait as inferred from a hydrodynamic model. Fish. Oceanogr. 5 (Suppl. 1): 58-70.

Hermann, A. J., Hinckley, S., Megrey, B. A. and P. J. Stabeno. 1996b. Interannual variability of the early life history of walleye pollock near Shelikof Strait, as inferred from a spatially explicit, individual-based model. Fish. Oceanogr. 5 (Suppl. 1): 39-57.

Hermann, A. J., Hinckley, S., Megrey, B. A and J. M. Napp. 2001. Applied and theoretical considerations for constructing spatially explicit Individual-Based Models of marine larval fish that include multiple trophic levels. ICES J. Mar. Sci. 58: 1030-1041

Hinckley, S., Hermann, A. J. and B. A. Megrey. 1996. Development of a spatially explicit, individual-based model of marine fish early life history. Mar. Ecol. Prog. Ser. 139: 47-68.

Hinckley, S., 1999. Biophysical mechanism sunderlying the recruitment process in walleye pollock (*Theragra chalcogramma*). PhD dissertation, University of Washington, Seattle, WA, USA, 258 pp.

Hsu, C. C. 1987. Spatial and temporal distribution patterns of female red king crabs in the southeastern Bering Sea. Dissertation. University of Washington, Seattle Washington, USA.

Huggett, J., Freon, P., Mullon, C., and Penven, P. 2003. Modelling the transport of anchovy *Engraulis encrasicolus* eggs and larvae in the southern Benguela: the effect of spario-temporal spawning patterns. Mar. Ecol. Prog. Ser. 250:247-262.

Hunt, G.L., Stabeno, P., Walters, G., Sinclair, E., Brodeur, R.D., Napp, J. and Bond, N. 2002. Climate change and control of the southeastern Bering Sea pelagic ecosystem. Deep-Sea Research(II), 49:5821-5853.

Incze, L. S., Armstrong, D. A. and S.L. Smith. 1987. Abundance of larval Tanner crabs (*Chionoecetes spp.*) in relation to adult females and regional oceanography of southeastern Bering Sea. Can, J. Fish. Aquat. Sci. 44:1143-1156.

Incze, L. S. and A. J. Paul. 1983. Grazing and predation as related to energy needs of stage I zoeae of the Tanner crab, *Chionoecetes bairdi* (Brachyura, Majidae). Biol. Bull. 165: 197-208.

Loher, T. 2001. Recruitment variability in southeast Bering Sea red king crab (*Paralithodes camtschaticus*): the roles of early juvenile habitat requirements, spatial population structure, and physical forcing mechanisms. Dissertation. University of Washington, Seattle, Washington, USA.

Loher, T. and D. A. Armstrong. 2005. Historical changes in the abundance and distribution of ovigerous red king crabs (*Paralithodes camtschaticus*) in Bristol Bay, Alaska, and potential relationship with bottom temperature. Fish. Oceanogr. 14: 292-306

Megrey, B.A., Hinckley, S. 2001. Effect of turbulence of larval fishes: a sensitivity analysis using and individual-based model. ICES Journal of Marine Science, 58:1015-1029.

Moore, A.M., H.G. Arango, E. Di Lorenzo, B.D. Cornuelle, A.J. Miller and D.J. Neilson, 2004: A comprehensive ocean prediction and analysis system based on the tangent linear and adjoint of a regional ocean model. Ocean Modelling, 7, 227-258.

Orensanz, J. L., B. Ernst, D. Armstrong, P. Stabeno, and P. Livingston. 2004. Contraction of the geographic range of distribution of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea: An environmental ratchet? CalCOFI Rep. 45: 65-79

Orensanz, J., Ernst, B., Armstrong, D. and A., Parma. 2005. Detecting early warnings of recruitment overfishing in male-only crab fisheries. In Fisheries Assessment and Management in Data-Limited Situations. Alaska Sea Grant College Program AK-SG-05-02. University of Alaska, Fairbanks. Alaska.

Overland, J.E. and P. Stabeno, 2004. Is the climate of the Bering Sea Warming and affecting the ecosystem? EOS, Transactaions American Geophysical union, 85(33):309-316.

Parada C., van der Lingen C.D., Mullon C. and P., Penven . 2003 Modeling the effect of egg buoyancy on anchovy recruitment success in the Southern Benguela: An IBM approach. Fish.Oceanogr. 12(3): 1-15

Parada, C., Mullon, C., Roy, C., Freon, P, Hutchings, L. and van der Lingen, C. Modeling the contribution of vertical migration to pre-recruitment success of anchovy early stages in the southern Benguela ecosystem (to be submitted).

Parada, C., Hinckley, S., Hermann, A., and Dorn, M. Hindcasting recruitment variability of walleye pollock in Gulf of Alaska based on an Individual-based model of early life history: relating physical and biological variables and model to data (In prep).

Paul, A.J. and J. M. Paul. 1980. The effect of early starvation on later feeding success of king crab zoeae. J. Exp. Mar. Biol. Ecol. 44: 247-251.

Paul, A. J., Paul, J. M. and K. O. Coyle. 1989. Energy sources for first-feeding zoeae of king crab *Paralithodes camtschatica* (Tilesius)(Decapoda, Lithodidae). J. Exp. Mar. Biol. Ecol. 130: 55-69.

Rugolo, L.J., Macintosh, R.A., Armistead, C.E., Haaga, J.A. and R.S., Otto. 2003. Report to industry on the 2003 Estearn Bering Sea Survey, Alaska Fisheries Science Center processed Rep 2003-11, National Marine Fisheries Service, Kodiak, Alaska.

Schumacher, J. D., and P. J. Stabeno. 1998. Continental shelf of the Bering Sea coastal segment. In The Sea, vol. 11, A. R. Robinson and K. H. Brink, eds. Hoboken, N.J.: John Wiley & Sons, pp. 789–822.

Shchepetkin, A.F., and J.C. McWilliams, 2005. The Regional Ocean Modeling System: A split-explicit, free-surface, topography-following coordinate ocean model, Ocean Modeling 9 (4): 347-404.

Somerton, D.A. 1981. Life history and population dynamics of two species of Tanner crab, *Chionoecetes bairdi* and *C.opilio*, in the eastern Bering Sea with implications for the management of the commercial harvest. Doctoral dissertation, University of Washington, Seattle.

Stabeno, P.J., Schumacher, J.D., Davis, R.F. and J.M. Napp. 1998. Under-ice observations of the water column temperature, salinity, and spring phytoplankton dynamics: eastern Bering Sea shelf. J. Mar. Res. 56: 239-255.

Stabeno, P. J., N. A. Bond, A. J. Hermann, C. W. Mordy and J. E. Overland. 2004. Meteorology and Oceanography of the Northern Gulf of Alaska. Prog. Oceanog. 24: 859-897.

Zheng, J. and Kruse, H. 2002. Recruitment patterns of Alaskan crabs in relation to decadal shifts in climate and physical oceanography. ICES, journal of Marine Science, 37:438-451.