NPRB Proposal Summary Page

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(To be filled in by applicant)

Project Title: Modeling study on the response of lower trophic level production to climate change

Project Period: From June 2006 To May 2008

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Research Priority and Subcategory:

Primary **1** Bering Sea Integrated Ecosystem Research Program
Secondary **2.b** Lower Trophic Level Productivity

Summary of Proposed Work (250 words or less):

The most prominent climate trends resulting from global climate warming in the southeastern Bering Sea, reduced sea ice cover and rising seawater temperature, have significant, profound impacts on lower trophic level production and fishery production. These impacts have aroused concerns in recent years and some explanatory hypotheses relating sea ice variability to marine ecosystems were proposed, such as the Oscillating Control Hypothesis (OCH, Hunt et al. 2002). Hypothesis testing has been hindered, however, because observational data describing productivity within sea ice are rare and coupled ice-ocean ecosystem models in the southeastern Bering Sea are lacking. The proposed study aims to establish a coupled ice-ocean ecosystem model including both pelagic and sea ice habitats. The model will be based on the existing pelagic ecosystem model (Jin et al. 2005b) for the southeastern Bering Sea and the ice-ocean ecosystem model (Jin et al. 2005a) for offshore Barrow. We will conduct sensitivity studies of the impact of physical and biological process variations on primary production, nutrient cycling, phytoplankton species composition, and carbon export to benthos. We will provide recommendations on how, when and which observations should be made to improve understanding of the Bering Sea ecosystem. Using historical observations from NOAA biophysical mooring site 2, a multi-year (1958-2005) model run is proposed to produce a long time series of biogeochemical model results. Seasonal variations and interannual changes in the results will be analyzed to elucidate the lower trophic level productivity response to climate changes.

Funding:

Total NPRB Funding Requested: **$149,547.00 (Univeristy of Alaska Fairbanks)**

Total Matching Funds Used: **$0.00**

Legally Binding Authorizing Signature and Affiliation:

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RESEARCH PLAN (max 12 pages, including tables and figures)

A. Project Title: (Provide a full and a suggested short title no more than 60 characters long)

Modeling study on the response of lower trophic level production to climate change
Short title: **Response of lower trophic production to climate change**

B. Proposal Summary:

The most prominent climate trends resulting from global climate warming in the southeastern Bering Sea, reduced sea ice cover and rising seawater temperature, have significant, profound impacts on lower trophic level production and fishery production. These impacts have aroused concerns in recent years and some explanatory hypotheses relating sea ice variability to marine ecosystems were proposed, such as the Oscillating Control Hypothesis (OCH, Hunt et al. 2002). Hypothesis testing has been hindered, however, because observational data describing productivity within sea ice are rare and coupled ice-ocean ecosystem models in the southeastern Bering Sea are lacking. The proposed study aims to establish a coupled ice-ocean ecosystem model including both pelagic and sea ice habitats. The model will be based on the existing pelagic ecosystem model (Jin et al. 2006b) for the southeastern Bering Sea and the ice-ocean ecosystem model (Jin et al. 2006a) for offshore Barrow. We will conduct sensitivity studies of the impact of physical and biological process variations on primary production, nutrient cycling, phytoplankton species composition, and carbon export to benthos. We will provide recommendations on how, when and which observations should be made to ensure effective improvement in understanding of the Bering Sea ecosystem. Using historical observations from National Oceanic and Atmospheric Administration (NOAA) biophysical mooring site 2, a multi-year (1958-2005) model run is proposed to produce a long time series of biogeochemical model results. Seasonal variations and interannual changes in the results will be used to elucidate the lower trophic level productivity response to climate changes.

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

The primary goal of this project aims at the priority 1 (Response of the Bering Sea Ecosystem to Climate Change), subcategory c (Is the lower trophic level production (quantity and form) changing in response to climate change? If so, how?).

The secondary goal of this project is the priority 2 (General research priorities on ecosystem components), subcategory b (lower trophic level productivity).

Our previous experience related to the proposed work include 1) pelagic ecosystem modeling studies in the southeastern Bering Sea (Deal et al. 2006; Jin et al. 2006b); 2) sea ice algal observations and coupled ice-ocean ecosystem modeling offshore Barrow (Jin et al. 2006a); 3) a coupled global atmosphere-sea ice-ocean model (1/6 degree meridional by 1/4 degree zonal) by the Center for Climate System Research (CCSR), the university of Tokyo; 4) the downscaled coupled ice-ocean model for the Bering Sea (1/12 degree meridional by 1/6 degree zonal); and 5) other climate research.

We believe the project's goal will be accomplished because of the PIs' combined, extensive expertise in ecosystem modeling of pelagic and sea ice algal habitats, and in climate research.

D. Project Design and Conceptual Approach

1. Introduction and background

It is now commonly understood that oceanic biology is an important component of the global climate system, yet many feedbacks between marine biogeochemistry and climate remain poorly understood. A great deal of progress has been made toward developing an understanding of physical forcing mechanisms and the response of biota over the broad shelf of the eastern Bering Sea. Research programs such as Process and Resources of the Bering Sea Shelf (PROBES), Inner Shelf Transfer and Recycling in the Bering and Chukchi Seas (ISHTAR), Bering Sea Fishery-Oceanography Coordinated Investigation (FOCI), Southeast Bering Sea Carrying Capacity (SEBSCC), Inner Fronts Study, and other ongoing programs, provide a wealth of observations and interpretations with respect to all elements of the conceptual model. The observations have revealed that the marine ecosystem of the Bering Sea has responded to climate changes that range from large-scale climate regime shifts (e.g. Hare and Mantua, 2000; Hunt et al., 2002) to small-scale episodic weather events (e.g. Bond and Overland, 2005).

The Oscillating Control Hypothesis (OCH), a widely recognized hypothesis proposed by Hunt et al. (2002), predicts that pelagic ecosystem function in the southeastern Bering Sea will alternate between primarily bottom-up control in cold regimes and primarily top-down control in warm regimes. Time series (1995-2001) from a biophysical mooring (Stabeno et al., 2001) in the middle domain of the southeastern shelf support the hypothesis that retreat of the winter sea ice before mid-March (or failure of ice to be advected into the region) results in an open water bloom in May or June in relatively warm water (>3ºC). Conversely, when ice retreat is delayed until mid-March or later, an ice-associated bloom occurs in cold (<0ºC) water in early spring (Hunt and Stabeno, 2002). These variations are important because the growth and production of zooplankton and the growth and survival of larval and juvenile fish are sensitive to water temperature.

The above hypotheses explained directly or indirectly some of the changes of primary production that have been observed in recent decades in response to climate changes, especially changes in the sea ice cover.During the cold years of the early 1970s, the predominant bloom occurred along the ice edge in the early spring accounting for a significant proportion of the annual carbon input over the shelf (Alexander and Niebauer, 1981). After the 1976/77 regime shift from “cold” to “warm”, peak primary productivity and phytoplankton biomass usually occurred during the open water bloom in May or June (Sambrotto et al., 1986; Whitledge et al., 1986) and the timing and magnitude of the spring phytoplankton bloom was found to correlate strongly with sea ice coverage in winter and spring (Niebauer et al., 1995; Stabeno et al., 1998). In cases of ice related blooms in March and April, the magnitude of the subsequent open water bloom was reduced in the southeastern Bering Sea middle shelf (Hunt et al., 2002). These changes have profound ‘bottom-up’ impacts on the abundance and species transitions of certain zooplankton and adult fish that are also impacted by the fishing activities in the region in a ‘top-down’ fashion. Sea ice related blooms in the eastern Bering Sea are important, not only because of their contribution to the annual primary production, but also because of their ability to affect the timing, magnitude and duration of the open water bloom later in the spring as mentioned in the above hypotheses. The controls of the sea ice ecosystem are still poorly understood compared to those of the water column ecosystem, due to scarce observations and complexities involving a number of environmental factors, such as ice types and the patchiness of snow and ice thickness distribution. The ice related blooms were observed from late April to May at the shelf break and middle shelf around and to the north of Pribilof islands in 1975-1977 (Alexander and Niebauer, 1981) and 1987-1988 (Niebauer et al., 1990, 1995). The data from biophysical mooring 2 (Figure 1), to the southeast of the Pribilof Islands, shows ice related blooms from mid-March to April and open water blooms in May in 1995-2000. Such a major ecosystem shift in the Northern Bering Sea was also reported by Grebmeier et al. (2006). A modeling approach is necessary to understand and examine the differences between these observations made at different locations and times (climate regimes).

To test the OCH hypotheses, we will investigate the underlying mechanisms by simulating and reproducing the biogeochemical and physical processes using a coupled ice-ocean ecosystem model. The existing lower trophic level ecosystem modeling studies in the eastern Bering Sea (e.g. Eslinger and Iverson, 2001; Merico et al., 2004; Jin et al., 2006b) considered the impacts of physical forcing on the pelagic ecosystem, but these ecosystem models did not include sea ice or ice algae components, and thus are inadequate for fully testing the OCH hypothesis.

We propose a coupled ice-ocean ecosystem modeling study to test the OCH and other hypotheses in the region to improve understanding of the feedbacks between marine ecosystem and climate; to quantify the response of this ecosystem to climate change; and to provide recommendations and guidance for future observations and modeling studies. Besides the large scale processes addressed by the OCH hypothesis, small scale processes relevant to the OCH hypothesis will also be investigated. For example, how do the ice algae move from the sea ice into the water, and within the water column? This is important because the under-ice blooms at mooring site 2 were observed at 12m under the sea surface. We have no information about the species comprising the bloom and their source; they could have come from the ice algae released from the ice bottom, or they could be adapted species that can grow in low light in the water. Before an investment is made in planning and carrying out more observations, these questions can be investigated by a series of designed model sensitivity studies which can be very helpful in deciding when, where, and which observations are needed. We plan to apply the model to the time series (1995-present) data of the NOAA/PMEL biophysical mooring site 2 (Figure 1) and other relevant data sets in the vicinity on which the OCH hypothesis is based.

The proposed coupled ice-ocean ecosystem model consists of the seawater ecosystem model and an ice algae ecosystem model. Our seawater ecosystem model was developed from the ecosystem models for the southeastern Bering Sea (Eslinger and Iversion, 2001) and a version with improved biological representations that was applied to Prince William Sound, Alaska (Eslinger et al., 2001). We rewrote the biological submodel for better coupling the biological model into ocean models (Wang et al., 2003). The biological submodel includes three nutrients, two phytoplankton species, three zooplankton species and one type of detritus (N3-P2-Z3-D). Later, Jin et al. (2006b) coupled the biological submodel with a 1-D physical model containing a level 2 ½ turbulence model (Mellor, 2001), and a tidal forcing term was added to enable realistic reproduction of the combined effects of wind mixing, tidal mixing and thermal mixing/stratification. The modified model is therefore called the International Arctic Research Center - Physical-Ecosystem Model (IARC-PhEcoM). IARC-PhEcoM was successfully applied to mooring site 2 in the Bering Sea and the effects of variations in the physical environment on the spring phytoplankton bloom were investigated (Jin et al., 2006b). The model was also applied to investigate the nitrogen dynamics and influence of physical and biological factors on the coccolithophore bloom (Deal et al. 2006). Some findings from our abovementioned model studies, such as the linkages of primary production and selective species abundance to the mixed layer depth (Jin et al. 2006b), will be of great importance for guiding the proposed model study. The innovative inclusion of combined effects of wind mixing, tidal mixing and thermal mixing/stratification in the IARC-PhEcoM physical model provides the tools essential to studying the influences of various physical processes on the lower-trophic primary production.

No sea ice algae ecosystem model has yet been reported for the southeastern Bering Sea; in situ observations of ice related blooms are rare, because of the difficulty of getting to the sea ice. There are few applications in other ice habitats that can be helpful for setting up ice algal ecosystem models in the Bering Sea. Arrigo et al. (1993) and Arrigo and Sullivan (1994) developed 1-D ice ecosystem models to simulate the growth behavior of the algal community in the fast ice of McMurdo Sound, Antarctica. Primary production of the Antarctic Ocean was estimated by applying the model to distinct locations (Arrigo et al. 1997). Nishi and Tabeta (2005) developed a coupled ice-ocean ecosystem model to study the contribution of ice algae to the ice-covered ecosystem of Lake Saroma of Japan, and found that ice algae released from the ice are rapidly exported because of their high sinking speed and the shallow depth of the lake. Carbon flows through the microbial food web of first-year ice in Resolute Passage (Canadian High Arctic) were inferred using an inverse model by Vezina et al. (1997). Based on biophysical ice core data collected in the landfast ice off Barrow, Alaska in the spring time of 2002 and 2003, Jin et al. (2006a) developed a coupled ice-ocean ecosystem model to study the factors controlling the landfast ice-ocean ecosystem, the processes which release ice algae from the ice bottom, the primary production of ice algae and the export of ice algae to benthos. In the absence of serial ice algal observations in the southeastern Bering Sea, revising the 1-D coupled ice-ocean ecosystem model offshore Barrow (Jin et al., 2006a) to apply to the southeastern Bering Sea is a natural choice, assuming that the Chukchi Sea shelf is the closest ice habitat with a series of observations.

The proposed ice-ocean ecosystem model study will focus on understanding the mechanisms of the ice-ocean ecosystem in the southeastern Bering Sea and their response to the climate changes. The results of this study will benefit other research programs in the region, such as the NSF Bering Sea Ecosystem Study (BEST) and is an important step towards future 3-D ice-ocean ecosystem modeling in the Arctic and sub-Arctic oceans.

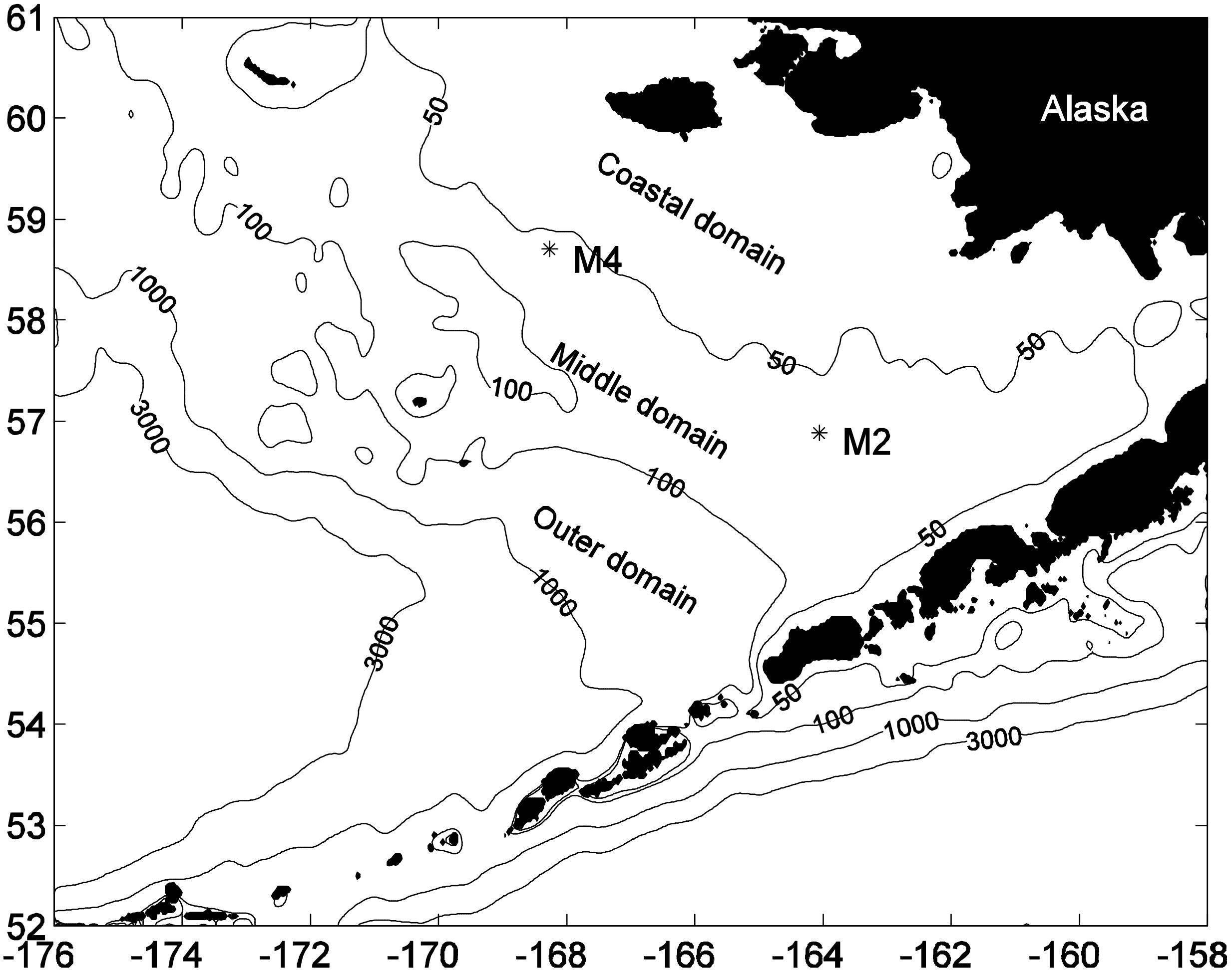

Figure 1: Topography of the southeastern Bering Sea. The NOAA/PMEL mooring sites 2 and 4 are denoted as M2 and M4. The PROBES mooring is in the vicinity of M2.

2. The proposed Ice-ocean ecosystem model

The proposed study will first establish a coupled ice-ocean ecosystem model for the southeastern Bering Sea on the basis of the existing seawater ecosystem model (Jin et al. 2006b; Deal et al. 2006) and ice-ocean ecosystem model (Jin et al. 2006a). The flow chart of the components in the proposed coupled ice-ocean ecosystem model is shown in Figure 2. The model equations and parameters are briefly described below and more details can be seen in Jin et al. (2006b), Deal et al. (2006) and Jin et al. (2006a).

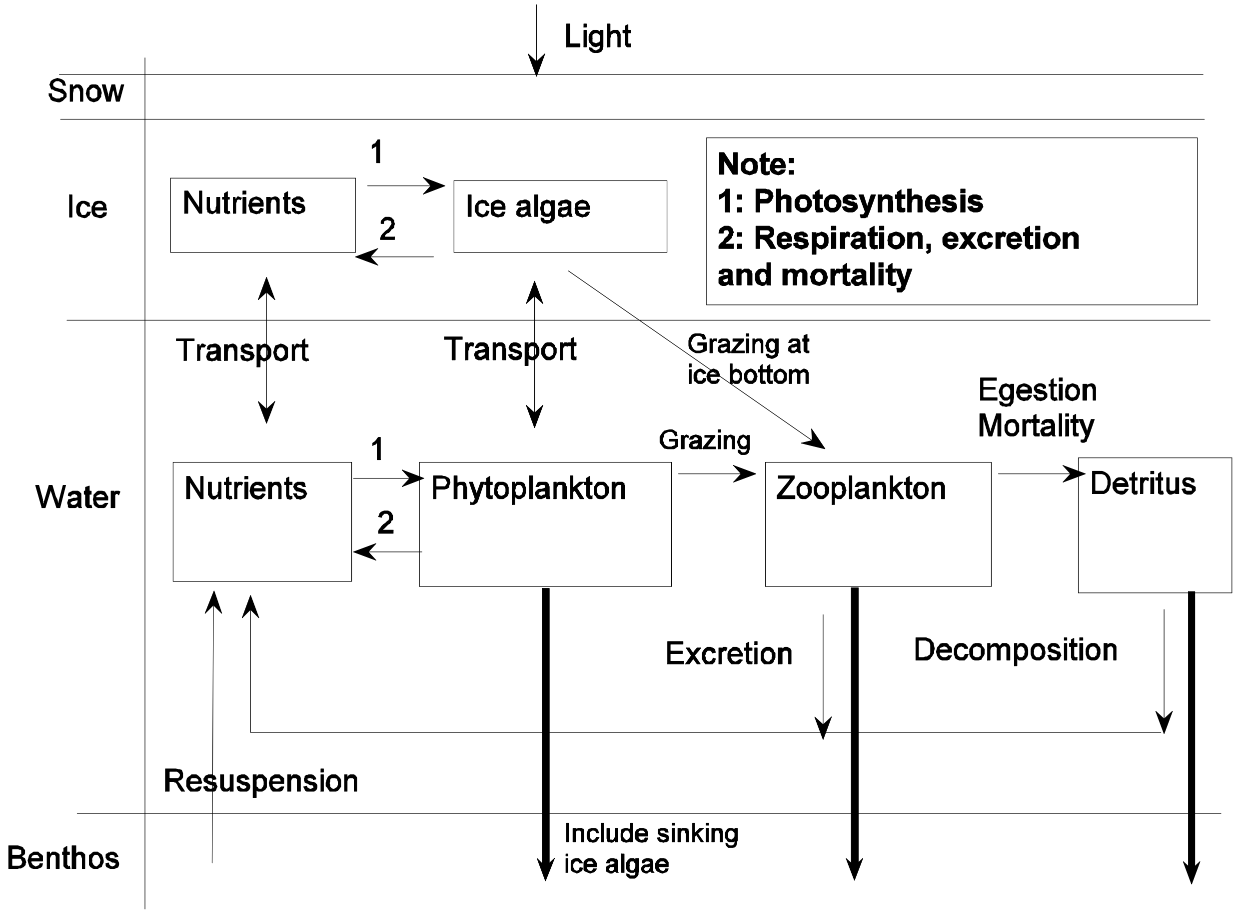

Figure 2: Flow chart of the components in the proposed coupled ice-ocean ecosystem model. Nutrients include nitrate/nitrate, ammonia and silicate; phytoplankton include diatoms and flagellates; zooplankton include small copepods, large copepods and microzooplankton.

1) Physical sub-model

The physical model includes the following one-dimensional prognostic equations of horizontal velocity (*U, V*), potential temperature (*T*), salinity (*S*), and turbulence components (qP^{2P}, $qP^{2P}l$) from a new version of the M-Y 2½ level turbulence model (Mellor, 2001):

$$\frac{DU}{Dt} - fV + \frac{1}{\rho_0}\frac{\partial p}{\partial x} = \frac{\partial}{\partial z}(K_M \frac{\partial U}{\partial z}) \tag{1}$$

$$\frac{DV}{Dt} + fU + \frac{1}{\rho_0}\frac{\partial p}{\partial y} = \frac{\partial}{\partial z}(K_M \frac{\partial V}{\partial z}) \tag{2}$$

$$\frac{DT}{Dt} = \frac{\partial}{\partial z}(K_H \frac{\partial T}{\partial z}) + \frac{\partial R}{\partial z} \tag{3}$$

$$\frac{DS}{Dt} = \frac{\partial}{\partial z}(K_H \frac{\partial S}{\partial z}) \tag{4}$$

$$\frac{Dq^2}{Dt} = \frac{\partial}{\partial z}(K_q \frac{\partial q^2}{\partial z}) + 2K_M[(\frac{\partial U}{\partial z})^2 + (\frac{\partial V}{\partial z})^2] + \frac{2g}{\rho_0}K_H\frac{\partial \tilde{\rho}}{\partial z} - 2\varepsilon \tag{5}$$

$$\frac{Dq^2 l}{Dt} = \frac{\partial}{\partial z}(K_q \frac{\partial q^2 l}{\partial z}) + E_1 l\{K_M[(\frac{\partial U}{\partial z})^2 + (\frac{\partial V}{\partial z})^2] + E_3\frac{g}{\rho_0}K_H\frac{\partial \tilde{\rho}}{\partial z}\} - l\varepsilon\tilde{W} \tag{6}$$

The surface boundary includes wind stress, heat and salt flux whose calculation involves the following meteorological variables: wind speed, cloud cover, air temperature, precipitation rate, sea level pressure, and specific (or relative) humidity. All of these variables are available from the National Center for Environmental Protection (NCEP) reanalysis data at 6-hourly time intervals provided by the NOAA Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/.

Sea ice thickness and concentration will come from other coupled 3-D ice-ocean climate models we are currently using for IARC projects. During times when ice is present, the surface water temperature will be set to freezing, and the shortwave radiation reaching the sea surface will be attenuated by snow and sea ice.

With the depth-averaged tidal current harmonic constants obtained from an Acoustic Doppler Current Profiler (ADCP), tidal forcing (T_x, T_y) in a depth-averaged barotropic tide can be obtained from the equations (1, 2):

$$T_x = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} = \frac{DU_T}{Dt} - fV_T + \mathrm{Cd} * U_T * \sqrt{U_T^2 + V_T^2}/\mathrm{H} \tag{7}$$

$$T_y = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} = \frac{DV_T}{Dt} + fU_T + \mathrm{Cd} * V_T * \sqrt{U_T^2 + V_T^2}/\mathrm{H} \tag{8}$$

where (U_T, V_T) are depth-averaged tidal current calculated from tidal current harmonic constants obtained from an ADCP (Jin et al. 2006b). The advantage of including tidal forcing in a 1-D physical model is to avoid some artificial mixing caused by parameterizations used by other 1-D models, such as those of Eslinger and Iverson (2001), Eslinger et al. (2001) and Merico et al. (2004).

2) Pelagic ecosystem sub-model

The 1-D model in seawater has a vertical resolution of 2m for both the physical and biological models. The model has nine compartments: two phytoplankton (diatom and flagellates: D and F), three zooplankton (small copepods, large copepods, and microzooplankton: ZS, ZL, ZP), three nutrients (nitrate+nitrite, ammonium, silicon: NOB_{3B}, NHB_{4B}, Si) and detritus (Det). We have changed one large zooplankton type in Eslinger et al. (2001) to microzooplankton, according to the fact that large zooplankton were rarely observed in the southeastern Bering Sea middle shelf. This biological submodel is coupled with the physical submodel described above. The vertical mixing coefficient KB_{HB} is used for all the biological variables according to the conventional understanding that a planktonic organism moves passively with the water. The vertical advection term is used only for compartments that can sink by themselves, such as phytoplankton and detritus. The nutrients are neutral in water so no sinking term is used. Tidal mixing is explicitly calculated in the model instead of the tidal parameterization used in Eslinger et al (2001). The biological model equations are expressed as follows:

$$\frac{\partial D}{\partial t}=D(G^D-R^D-Rg^D)-\Gamma^{DS}ZS-\Gamma^{DL}ZL-\Gamma^{DP}ZP+\frac{\partial(W^D D)}{\partial z}+\frac{\partial}{\partial z}(K_H\frac{\partial D}{\partial z}) \tag{9}$$

$$\frac{\partial F}{\partial t}=F(G^F-R^F-Rg^F)-\Gamma^{FS}ZS-\Gamma^{FL}ZL-\Gamma^{FP}ZP+\frac{\partial(W^F F)}{\partial z}+\frac{\partial}{\partial z}(K_H\frac{\partial F}{\partial z}) \tag{10}$$

$$\frac{\partial ZS}{\partial t}=ZS[A^S(\Gamma^{DS}+\Gamma^{FS}+\Gamma^{AiS})(1-Ex^S)-M^S]+\frac{\partial}{\partial z}(K_H\frac{\partial ZS}{\partial z}) \tag{11}$$

$$\frac{\partial ZL}{\partial t}=ZL[A^L(\Gamma^{DL}+\Gamma^{FL}+\Gamma^{AiL})(1-Ex^L)-M^L]+\frac{\partial(W^L ZL)}{\partial z}+\frac{\partial}{\partial z}(K_H\frac{\partial ZL}{\partial z})$$

$$\frac{\partial ZP}{\partial t}=ZP[A^P(\Gamma^{DP}+\Gamma^{FP}+\Gamma^{AiP})(1-Ex^P)-M^P]+\frac{\partial}{\partial z}(K_H\frac{\partial ZP}{\partial z}) \tag{12}$$

$$\frac{\partial NO_3}{\partial t}=-f_{NO3}[D(G^D-R^D)+F(G^F-R^F)]+C_{AtoN}\cdot NH_4+\frac{\partial}{\partial z}(K_H\frac{\partial NO_3}{\partial z}) \tag{13}$$

$$\begin{aligned}\frac{\partial NH_4}{\partial t}&=ZS\cdot A^S(\Gamma^{DS}+\Gamma^{FS})Ex^S+ZL\cdot A^L(\Gamma^{DL}+\Gamma^{FL})Ex^L\\&+ZP\cdot A^P(\Gamma^{DM}+\Gamma^{FM})Ex^M+D\cdot Rg^D+F\cdot Rg^F+Det\cdot Rg^{Det}\\&-\left(1-f_{NO_3}\right)[D(G^D-R^D)+F(G^F-R^F)]-C_{AtoN}\cdot NH_4+\frac{\partial}{\partial z}(K_H\frac{\partial NH_4}{\partial z})\end{aligned} \tag{14}$$

$$\frac{\partial Si}{\partial t}=-\kappa_{Si}[D(G^D-R^D)]+\frac{\partial}{\partial z}(K_H\frac{\partial Si}{\partial z}) \tag{15}$$

$$\begin{aligned}\frac{\partial Det}{\partial t}&=ZS\cdot[(1-A^S)(\Gamma^{DS}+\Gamma^{FS})+M^S]+ZL\cdot[(1-A^L)(\Gamma^{DL}+\Gamma^{FL})+M^L]\\&+ZP\cdot[(1-A^P)(\Gamma^{DP}+\Gamma^{PM})+M^P]-Det\cdot Rg^{Det}+\frac{\partial(W^{Det}Det)}{\partial z}+\frac{\partial}{\partial z}(K_H\frac{Det}{\partial z})\end{aligned} \tag{16}$$

where superscripts *D* and *F* denote diatoms and flagellates. Superscript *Ai* denotes ice algae in the grazing terms ($\Gamma^{AiS},\Gamma^{AiL},\Gamma^{AiP}$) that represent surface layer zooplankton grazing on the ice algae at the ice bottom and zooplankton grazing at other depths on the sinking ice algae released from sea ice into the sea water. Superscripts *S*, *L*, and *P* denote small copepods, large copepods, and micro-zooplankton. Terms *G, R,* and *Rg* are phytoplankton growth rate, respiration rate, and mortality rate, respectively (details in Jin et al., 2006b). Modifications and improvements over Eslinger at al. (2001) are summarized below:

- The vertical mixing coefficient *KB*$_{HB}$ is used in each equation.
- A nitrification term is included in the nitrogen and ammonium equations. Ammonium is converted to nitrogen at a rate of C_{AtoN} *=6.25×10P^{-4P} hP^{-1P} (=1.5% dP^{-1P}).*
- Silicon losses due to uptake are restored back to the bottom layer instantly, which is important for conserving the nutrients so that the model can run longer than one season.
- Maximum phytoplankton growth rate at *0°C* used in equations (23a) and (23b), (μ_0^D,μ_0^F) for both diatoms and flagellates equaled *0.06hP*$^{-1P}$ in Eslinger et al (2001), while in Merico et al. (2004) these rates were *1.2 dP*$^{-1P}$ and *0.65 dP*$^{-1P}$, respectively (*=0.05 hP*$^{-1P}$*, 0.027 hP*$^{-1P}$). Observations in the

Southeastern Bering Sea indicate that diatoms dominate spring bloom. Thus, in this study, we used the same μ_0^D to μ_0^F ratio as in Merico et al. (2004), but chose to increase the values slightly to *0.07* hP^{-1P} and *0.038* hP^{-1P} through model-data comparisons using different values of μ_0^D and μ_0^F.

3) Ice algal ecosystem model

The sea ice ecosystem model focuses on the bottom 2cm skeletal layer which is observed in sea ice habitats. Generally speaking, the greatest fraction of sea ice algae reside in the bottom layer of sea ice because of the stable environment there that is favorable for growth. The upward distribution of ice algae is limited by nutrient availability and the high brine salinity characteristic of the sea ice interior when temperatures are low (Arrigo and Sullivan, 1992). Platelet ice is uncommon in the Arctic and sub-Arctic region; thus it is not considered in this study.

Due to lack of observations, Arrigo et al. (1993) parameterized zooplankton grazing in a similar mathematical form as respiration, which is actually equivalent to increasing the respiration coefficient. The grazing term is omitted in Jin et al. (2006a) due to low levels of grazing observed offshore Barrow. Since we do not know how important grazing is in the eastern Bering Sea shelf, a term representing grazing on the ice-algal standing stock at the ice bottom will added in the proposed study. The biological dynamics in the sea ice are expressed as follows:

$$\frac{\partial Ai}{\partial t} = Ai(G^{Ai} - R^{Ai} - Rg^{Ai}) - \Gamma^{AiS} ZS - \Gamma^{AiL} ZL - \Gamma^{AiP} ZP + \frac{\partial (T_{wi} - W^{Ai})Ai}{\partial z} + \frac{\partial}{\partial z}(K_{wi}\frac{\partial Ai}{\partial z}) \tag{17}$$

$$\frac{\partial NO_3}{\partial t} = N_{Nit}[NO_3^{Ai}] - f_{NO3} Ai(G^{Ai} - R^{Ai}) + \frac{\partial T_{wi} NO_3}{\partial z} + \frac{\partial}{\partial z}(K_{wi}\frac{\partial NO_3}{\partial z}) \tag{18}$$

$$\begin{aligned}\frac{\partial NH_4}{\partial t} &= Ai\, Rg^{Ai} - (1 - f_{NO3})\, Ai(G^{Ai} - R^{Ai}) - N_{Nit}[NH_4^{Ai}] \\ &+ \frac{\partial T_{wi} NH_4}{\partial z} + \frac{\partial}{\partial z}(K_{wi}\frac{\partial NH_4}{\partial z})\end{aligned} \tag{19}$$

$$\frac{\partial Si}{\partial t} = - k_{Si} Ai(G^{Ai} - R^{Ai}) + \frac{\partial T_{wi} Si}{\partial z} + \frac{\partial}{\partial z}(K_{wi}\frac{\partial Si}{\partial z}) \tag{20}$$

where Ai denotes ice algal biomass in units of mmol N/m^3, and NO$_3$, NH$_4$, and Si are nutrients in units of mmol N/m^3, mmol N/m^3 and mmol Si/m^3, respectively. $N_{frac}, Si_{frac}, I_{frac}$ are ratios expressing nitrogen, silicon and light limitation. Term ξ is an empirical salinity-dependent ice algal growth rate calculated as in Arrigo and Sullivan (1992). Terms G^{Ai}, R^{Ai}, Rg^{Ai} are ice algal growth rate, respiration rate, and mortality rate, respectively (Jin et al. 2006a).

Brine flux volume in the skeletal layer has a high correlation (R^2=0.994) with ice growth rate (dH_{ice}/dt) during the ice growth period (Wakatsuchi and Ono, 1983). The water-ice interface transport T_{wi} is therefore calculated using the relationship described in Arrigo et al. (1993).

The light attenuation coefficients are 20m^{-1} for snow, 5m^{-1} for the top 10cm of ice and 1m^{-1} for ice below 10cm (based on Perovich 1996; H. Eicken, personal communications). The ice algae self-shading coefficient is 0.005m^2 (mmol N)$^{-1}$.

3. Proposed Work

The proposed study will first establish a coupled ice-ocean ecosystem model for the southeastern Bering Sea, then apply the model to decade-long time series data from the NOAA/PMEL biophysical mooring sites 2 and 4 (Figure 1) and try to examine the question of how the lower trophic level ecosystem changes in response to climate change. Comparisons of the modeling results at the two mooring sites along with previous observations of ice related blooms (Alexander and Niebauer, 1981, Niebauer et al., 1990, 1995) can help answer the question of how the role of sea ice differs from north to south over the shelf. The proposed work is described in detail as follows:

1) We will use the historical observational data (both physical and biological) to further validate the coupled ice-ocean ecosystem models for the multi-year runs in additional to what we have already done at M2 site for year 2000 (Jin et al., 2006b) and offshore Barrow for years 2002-2003 (Jin et al., 2006a). The model parameters will be tuned to the southeastern Bering Sea, e.g., the ice algal growth rate, transport between the water-ice interfaces, zooplankton grazing rate on the ice algae, sinking velocity of ice algae in water, etc. For example, observations of primary productivity (Alexander and Niebauer, 1981; McRoy and Goering, 1974) and species composition of ice algal assemblages from early studies in the Bering Sea (Schandelmeier and Alexander, 1981) and for similar marine algal types and regions of the Arctic (e.g. Horner and Alexander, 1972; Kirst and Weincke, 1995) will be utilized. In situ observations of chlorophyll under the ice made by Alexander and Niebauer (1981) indicate an ice related bloom in late April to May in 1975-1977, in contrast to the ice related bloom in mid-March to April and open water bloom in May from the M2 mooring site in 1995-2000 (Hunt et al., 2002). The timing and magnitude of the ice related bloom relative to open water bloom will be pursued through modeling and collaborations with observationalists. There are also a few studies that can provide time-series data including water temperature, salinity, chlorophyll, nutrient concentration and primary production from hydrographic cross-sections through the ice-edge (Niebauer and Alexander, 1985; Niebauer et al., 1990) and by drifting with the water in the marginal ice zone (Niebauer et al., 1995) in the 1980's. Early data also indicate that zooplankton numbers and grazing rates were low during the ice-edge spring bloom (Cooney and Coyle, 1982; Coyle and Cooney, 1988). More recent data from NOAA's Fisheries-Oceanography Coordinated Investigations and Southeast Bering Sea Carrying Capacity Program (Macklin and Hunt, 2004) add to our knowledge of zooplankton abundance and grazing, and will be useful for model validation. Microzooplankton have been observed in the spring (Howell-Kűbler et al., 1996) and summer (Olson and Strom, 2002) on the Bering Sea shelf. The historical literature provides snapshots from the last few decades consisting of distinct periods separated by ”regime shifts” in the winter of 1976-77, 1988-1989 (Hare and Mantua, 2000) and 1997/1998 (Hunt et al., 2002). In order to sort out the differences between these periods, we will synthesize all relevant historical observational data from the Bering Sea and Arctic to critically calibrate and validate the model. In this way we may also help to guide sampling designs by pointing out important gaps in understanding where and when observations are needed. Our modeling studies off Barrow have highlighted the need for an understanding of exchange processes at the water-ice interface and a quantitative understanding of ice algal attachment to ice and particle flux out of the ice (Jin et al., 2006a). The data we will use also include the PROBES station data, data from the NOAA/PMEL mooring sites 2 and 4, data from the World Ocean Atlas (WOA2001, from the NOAA web site), Sea-viewing Wide Field-of-view Sensor (SeaWiFS) chlorophyll a concentration data, Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) data and various ship-board cruise data, such as the T/S Oshoro Maru time series of zooplankton abundance. Most of these data were obtained during open water conditions and ice related blooms were only captured by the 12m-depth fluorometer in 1995, 1997 and 1999 at mooring 2 (Hunt et al., 2002). Thus, some parameters in the ice algal ecosystem submodel will have to be adapted from similar model applications in other comparable ice habitats and all other parameters will be given best-fit values according to the limited model-data comparison. As the project progresses into 2007 and 2008, we intend to continuously update our model parameters as data become available through publications, collaborations, and NPRB partnerships with other agencies and institutions in the Climate Change and Bering Sea Ecosystem consortium, which includes the NSF's BEST and NOAA's Alaska Science and Fisheries Service and PMEL.

2) We will conduct sensitivity studies of the impacts of physical and biological process variations on the quantity and timing of primary production, nutrients cycling, species composition of phytoplankton, carbon export to benthos, etc. Those process variations include variations in timing of sea

ice cover, sea ice thickness and concentration, water temperature, regeneration of nutrients, resuspension of nutrients from benthos, etc. The ephemeral nature of the Bering Sea ice poses a challenge while adapting the ice ecosystem model from fast ice offshore Barrow to the Bering Sea. In order to model the ice related bloom, we need to reproduce the favorable physical environment: stratification caused by freshwater from melting ice, as described in the previous observations. The initial ice algal biomass in the sea ice that seeds the bloom will be derived from available observations in the Bering and Chukchi Sea regions. The effects of the interannual variance of the seeding concentration on the bloom will have to be examined through sensitivity studies. Other currently unknown processes will also be explored with sensitivity studies. For example, a bloom 12m deep beneath the sea ice was captured by the NOAA/PMEL biophysical mooring M2 in several years (e.g. 1995, 1997, 1999), but no concurrent measurement of sea ice and ice algae were made to identify the species composition and mechanism of the bloom. Whether it is due to released ice algae from the loose/melting bottom of the sea ice or whether it is due to certain adaptive species that can grow in the icy seawater environment remains an open question. The numerical model studies can be designed to explore various possibilities, and thus reduce the time and effort that must be devoted to making expensive observations in the field. With these numerical studies, we will find out how predictive the model is for currently available observations, and in what ways the model needs to be improved. We will provide recommendations on how, when and which observations can most effectively be made to ensure that they contribute to improving our understanding of the Bering Sea ecosystem.

3) We will conduct a multi-year (1958-2005) model run for the NOAA/PMEL mooring site 2 using the optimized model parameters obtained in the first step. Observational time series are only available during the PROBES project time period (1981-1982, Eslinger and Iverson, 2001) and during the mooring 2 operational time period (from 1995 to present). The atmospheric forcing is either the 6-hourly NCEP reanalysis data, or the mooring observational data with data gaps filled by NCEP data. Our focus will be on the period with observations, especially when mooring 2 data are available, because this time period contains both cold years with sea ice cover (e.g. 1995, 1997, 1999) and warm years without sea ice cover (e.g., 1996, 1998, 2000-2005). The most prominent climate trends resulting from global climate warming in the southeastern Bering Sea, reduced sea ice cover and rising sea water temperature, are also significant during this time period. Since sea ice concentration and thickness were not measured, we will use other climate model outputs, either from the CCSR coupled global atmosphere-sea ice-ocean model (1/6 degree meridional by 1/4 degree zonal) or the downscaled coupled ice-ocean model for the Bering Sea (1/12 degree meridional by 1/6 degree zonal). Both models are currently supported by IARC and are available at no charge for the work proposed here.

4) The results of the multi-year run, e.g. the modeled ice algal and phytoplankton primary production, mixed-layer depth, nutrients concentrations etc., will be compared with observations. Statistical correlations between the model and data will be analyzed to seek response of the ecosystem variability to the climate variability from both large-scale climate patterns (Pacific Decadal Oscillation (PDO), Arctic Oscillation (AO) index etc.) to small local scale physical environment variability (sea ice cover, water temperature, wind, net short wave radiation etc.). Similar statistics will also be conducted to examine the impacts of the lower trophic level variability on the variability of fish harvest in the region.

E. Project Management

Personnel

The P.I., Dr. Meibing Jin, will manage and oversee the project. Since coming to the University of Alaska, Fairbanks (UAF) in 1998, Dr. Jin has been co-PI on six funded and successfully completed projects. He is currently co-P.I. (Dr. Jia Wang is P.I.) of an ongoing project funded by the Mineral Management Service (MMS), and involving IARC-funded research on global climate warming assessment and development of a high-resolution global coupled atmosphere-sea ice-ocean model and a polar region ecosystem model. Dr. Jin has a strong research background in lower trophic level ecosystem modeling in both pelagic and sea ice habitats, and also in climate modeling research; his experience will be essential to accomplishing the goals of this proposal. In this study, Dr. Jin will be responsible for developing and validating the coupled ice-ocean ecosystem model in the southeastern Bering Sea, designing the model sensitivity studies, and conducting the multi-year run for mooring site 2.

Co-P.I. Dr. Clara J. Deal will collect observational data for the validation of the model, and will work with Dr. Jin on model initial conditions, forcing data preparation, design and analysis of the model sensitivity studies and the multi-year run. Dr. Deal has a strong background in biological modeling and observations. She will coordinate with other scientists on using historical observation data to represent pelagic and sea ice algal ecosystems in the Alaskan waters. These collaborators include the following co-authors and acknowledged contributors in Jin et al. (2006b) and Jin et al. (2006a): Dr. Stabeno (PMEL, NOAA), Dr. Whitledge (Institute of Marine Science (IMS), UAF), Dr. Gradinger (IMS, UAF), Dr. Eslinger (NOAA), and Dr. Krembs (Applied Physics Lab (APL), University of Washington (UW)); and others.

Co-P.I. Dr. Jia Wang will work with Dr. Jin on linking multi-year model results to climate variability. Dr. Wang has a strong record of publications in climate research and coupled sea ice-ocean modeling, and he is currently the group leader for the Arctic ocean/sea ice research theme at IARC. His expertise will benefit our search for the climate impacts of climate change, from global scale pattern changes to local small scale environmental changes, on the Bering Sea ecosystem.

A summer student assistant (to be determined) will work on data and model results analysis and educational outreach.

Schedule/milestones

Task 1. Coupled ice-ocean ecosystem model setup and validation for the southeastern Bering Sea: June to September 2006.

Task 2. Sensitivity studies of varying physical and biological processes: August 2006 to August 2007.

Task 3. Multi-year model run: October 2006 to October 2007.

Task 4. Search for response of primary production to climate changes: November 2006 to February 2008.

Writing two journal papers: January 2007 to May 2008.

Writing project reports: February 2008 to May 2008.

F. Project Costs

See the included budget. The budget justification is as follows:

Salaries and benefits:

Personnel: Funding to support 2 months of salary for 2 years is requested for the Principal Investigator, M. Jin, to administer the project. A total of one month of support for Co-PIs C. Deal and J. Wang are requested to perform the proposed research. Faculty receive leave benefits at a rate of 1.1%, calculated on salary. We are also requesting funding for one summer student assistant for 3 mos. per year to assist in research and educational outreach. Salary costs reflect 2005 salaries, plus a 5.0% increase per year. Staff benefits are applied according to UAF’s provisional benefit rates for FY06. Rates are 35.5% for faculty and 8.7% for graduate students (summer only). These rates also have an inflation factor built in, based on previous years’ increases.

Travel: Funding for one trip to the January science symposium in Anchorage is requested each year during the contracted period of the project. This includes round trip air fare, 5 nights of hotel, and 7 days of per diem per UA Board of Regents regulations for Alaska in-state travel. One round trip to San Francisco for the American Geophysical Union (AGU) meeting is requested for both years as well. This includes 5 nights of hotel and 7 days of per diem in accordance with GSA/JTR Regulations. Lastly, funding for one trip is requested to attend the annual January symposium in Anchorage following the end of the contracted period to present results. This includes 5 nights of hotel and 7 days of per diem per UA Board of Regents regulations for Alaska in-state travel.

Material and Supplies: A total of $4000 is requested for equipment and supplies. This includes $2000 for project supplies, and $2000 for a laptop computer.

Publication and reports: A total of $6000 is requested, $4000 to cover costs associated with publishing 2 journal papers, and $2000 for printing the reports

Education and outreach: $2000 as required by the NPRB. After we have completed our initial data analysis and manuscript preparation, we will provide the data and results on an internet site to the public at large to use in future studies, be these high-school projects or professional-level research.

Indirect Costs: Facilities and Administrative (F&A) costs are calculated at 29.8% Modified Total Direct Cost (MTDC) for the International Arctic Research Center. MTDC includes total direct costs minus tuition, stipends, scholarships, subaward amounts over $25,000, participant support costs, and equipment.

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