



Ice-associated phytoplankton blooms in the southeastern Bering Sea

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[1] Ice-associated phytoplankton blooms in the southeastern Bering Sea can critically impact the food web structure, from lower tropic level production to marine fisheries. By coupling pelagic and sea ice algal components, our 1-D ecosystem model successfully reproduced the observed ice-associated blooms in 1997 and 1999 at the NOAA/PMEL mooring M2. The model results suggest that the ice-associated blooms were seeded by sea ice algae released from melting sea ice. For an ice-associated bloom to grow and reach the typical magnitude of phytoplankton bloom in the region, ice melting-resulted low-salinity stratification must not be followed by a strong mixing event that would destroy the stratification. The ice-associated blooms had little impacts on the annual primary production, but had significant impacts in terms of shifting phytoplankton species, and the timing and magnitude of the bloom. These changes, superimposed on a gradual ecosystem shift attributed to global warming, can dramatically alter the Bering Sea ecosystem. **Citation:** Jin, M., C. Deal, J. Wang, V. Alexander, R. Gradinger, S. Saitoh, T. Iida, Z. Wan, and P. Stabeno (2007), Ice-associated phytoplankton blooms in the southeastern Bering Sea, *Geophys. Res. Lett.*, *34*, L06612, doi:10.1029/2006GL028849.

1. Introduction

[2] The southeastern Bering Sea shelf is one of the most productive ecosystems in the world [Springer *et al.*, 1996]. The high open-water productivity is modulated by seasonal sea ice cover advected from the north. The climate trends of reducing ice cover and rising temperature have already caused a major ecosystem shift in the northern Bering Sea [Grebmeier *et al.*, 2006]. During the cold years of the early 1970s the predominant phytoplankton 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 shift from “cold” to “warm” regime, primary productivity and phytoplankton biomass usually peaked later in the season during the open water phase in May/June. Ice-associated production was captured by fluorometer at the

National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory (NOAA/PMEL) mooring M2 (Figure 1) in late March to May of 1995, 1997 and 1999 [Hunt and Stabeno, 2002] since its deployment from 1995. These years overlapped with the unexpected and dramatic declines of AYK (Arctic-Yukon-Kuskokwim) salmon runs that prompted 15 federal and state disaster declarations from 1997 to 2002. Relationships, if any, between the ice-associated bloom and the ecosystem shift were still unclear. Highlighting the relevance of the timing of the sea ice cover retreat, Hunt *et al.* [2002] proposed an Oscillating Control Hypothesis (OCH): pelagic ecosystems 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 from M2 [Stabeno *et al.*, 2001] 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 (>3°C). Conversely, when ice retreat is delayed until mid-March or later, an ice-associated bloom occurs in cold (<0°C) water in early spring [Hunt and Stabeno, 2002].

[3] Although ice-associated blooms are critical to the Bering Sea ecosystem, they remain understudied in terms of observation and modeling. Previous ecosystem models for this region applied only to open water blooms. Few ecosystem models with sea ice algal have been applied to other regions, e.g., Antarctica by Arrigo *et al.* [1993] and Arrigo and Sullivan [1994]; Lake Saroma, Japan by Nishi and Tabeta [2005]; and the landfast ice off Barrow, Alaska by Jin *et al.* [2006b]. In this study, we coupled an ice algal submodel [Jin *et al.*, 2006b] with the pelagic submodel [Jin *et al.*, 2006a] in the southeastern Bering Sea. We emphasize the ice-associated pelagic bloom rather than the ice algal bloom within sea ice.

[4] Limited by both satellite and mooring data availability, this study focused on the simulation and validation of the ice-associated blooms in 1997 and 1999. These two years are representative of different large scale climate features and dramatic ecosystem changes in the Bering Sea [Hunt and Stabeno, 2002]. The major influential Pacific Decadal Oscillation (PDO) [Zhang *et al.*, 1997] climate index in the region switched from a positive phase in 1997 to a negative phase in 1999 (Figure 1b). The year 1997 had long and calm summer with a warm upper mixed layer. In contrast, 1999 was characterized by cold temperatures, late ice retreat, stormy weather and climate indices all similar to those from the early 1970s, before the major climate shift occurred in 1976/77 [Hunt and Stabeno, 2002].

2. Methods

[5] The 1-D coupled ice-ocean ecosystem model consists of the seawater ecosystem model based on the Physical-

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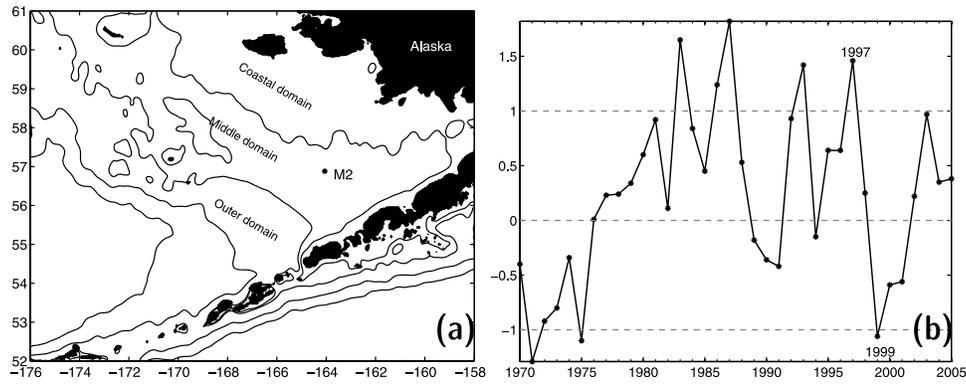


Figure 1. (a) Model domain: The NOAA/PMEL mooring 2 is marked as M2. (b) PDO index.

Ecosystem Model (PhEcoM) [Wang *et al.*, 2003; Jin *et al.*, 2006a] and an ice algae ecosystem model adapted from Jin *et al.* [2006b]. The model has ten compartments: three phytoplankton (pelagic diatom, flagellates and ice algae: D, F and Ai), three zooplankton (copepods, large zooplankton, and microzooplankton: ZS, ZL, ZP), three nutrients (nitrate+nitrite, ammonium, silicon: NO_3 , NH_4 , Si) and detritus (Det). Ice algae retained their photosynthetic parameters (light saturation and light inhibition) after release into the water column [Jin *et al.*, 2006b]. Their growth rate will be discussed later in the sensitivity cases. Zooplankton grazing parameters on released algae were set to be the same as for diatoms because Arctic ice algal bottom communities are mostly dominated by diatoms [Gradinger, 1999]. The model was applied to the M2 site (Figure 1a, water depth = 74 m) and run from 1995 to 2000. There were 37 vertical layers in the water, each 2m thick, and one ice algae layer of 2cm at the bottom of the ice. The sea ice thickness was calculated based on the ice concentration from the National Snow and Ice Data Center (NSIDC) Special Sensor Microwave/Imager (SSM/I) (<http://nsidc.org/data/seaice>) multiplied by 1.2 m. Snow depth was assumed to be zero. The model results for the water column productivity, which were our most concern, were not sensitive to variations in the number 1.2 m (e.g. 1.2 ± 0.2 m, the ice algal concentration in the surface in 1997 reached the maximum at the same time and only varied by 0.05%). The physical model was forced by tides, wind, shortwave radiation, surface heat and salt flux, and restored to available observed daily sea surface temperature (SST) and salinity (SSS). The National Centers for Environmental Protection (NCEP) wind, cloud cover, air temperature, precipitation rate, sea level pressure, and specific humidity were used to calculate the surface fluxes [Jin *et al.*, 2006a]. Shortwave radiation reaching the sea surface was the ice concentration-weighted average of radiation with and without sea ice attenuation.

[6] Initial velocity of the physical model was set to zero. Initial temperature and salinity conditions were taken from the M2 data. Initial conditions for the pelagic biological model were based on historical measurements and the National Oceanographic Data Center's (NODC's) World Ocean Atlas (WOA) 2001 climatology nitrate data as in the work by Jin *et al.* [2006a]. Initial sea ice algae were assumed to be brought to the mooring site by the sea ice, and when sea ice concentration first went above 15%, initial

sea ice algae concentration was set to be $0.05 \text{ mmol N m}^{-3}$ in the water (this value was tested and found to be not sensitive to smaller values) and 13 mmol N m^{-3} in the sea ice based on results from Jin *et al.* [2006b].

[7] It has long been believed that the ice-edge algal bloom results from stratification due to low-salinity melt water; another important question is whether the bloom is seeded by ice algae released from melting ice. Such a seeding of the water column algal bloom has been reported in both polar regions [e.g., Alexander and Niebauer, 1981; Schandelmeier and Alexander, 1981; Garrison *et al.*, 1987], but exceptions have also been reported [Bianchi *et al.*, 1992]. Thus, two cases were studied here. In case one, we proposed that ice algal growth rate G^{Ai} in the water column decreases with increasing water temperature:

$$G^{Ai} = \mu_0^{Ai} e^{T_{freeze}-T} \times \min(N_{frac}, Si_{frac}, I_{frac}) \xi \quad (1)$$

where μ_0^{Ai} is maximum growth rate at 0°C , and N_{frac} , Si_{frac} , I_{frac} are ratios of nitrogen, silicon and light limitation. Term ξ is an empirical salinity-dependent ice algal growth rate [Arrigo and Sullivan, 1992]. These variables have the same definitions and values as in the work by Jin *et al.* [2006b]. In case two, G^{Ai} is set to zero.

[8] T_{freeze} and T are freezing temperature and water temperature, respectively. Short-time (several hours) lab incubations showed that ice algae might grow in warm water up to 14°C , with a wide range of optimal growth temperatures (-0.5°C to 8°C) for sea ice algae in the Arctic [Rochet *et al.*, 1985; Michel *et al.*, 1989] and Antarctic [Arrigo and Sullivan, 1992]. However, in the field, Horner and Schrader [1982] found that ice algal cells released from the ice into the water column were only marginally productive and that the relatively high water column productivity at the end of the ice algal bloom did not last. Because after a short time in the water column these cells became unhealthy and were no longer productive, possibly due to the higher temperatures or other unknown challenges preventing adaptation to the water column environment. Likewise, spring phytoplankton blooms in areas on the southeastern Bering Sea shelf are not dominated by ice algae [Sukhanova *et al.*, 1999], indicating an inability of ice algae to thrive in the warm water. Thus, in equation (1) we parameterize the influence of the water column environment as reduced ice algal growth rate with increased temperature. This temperature dependency is also substantiated by reported maxi-

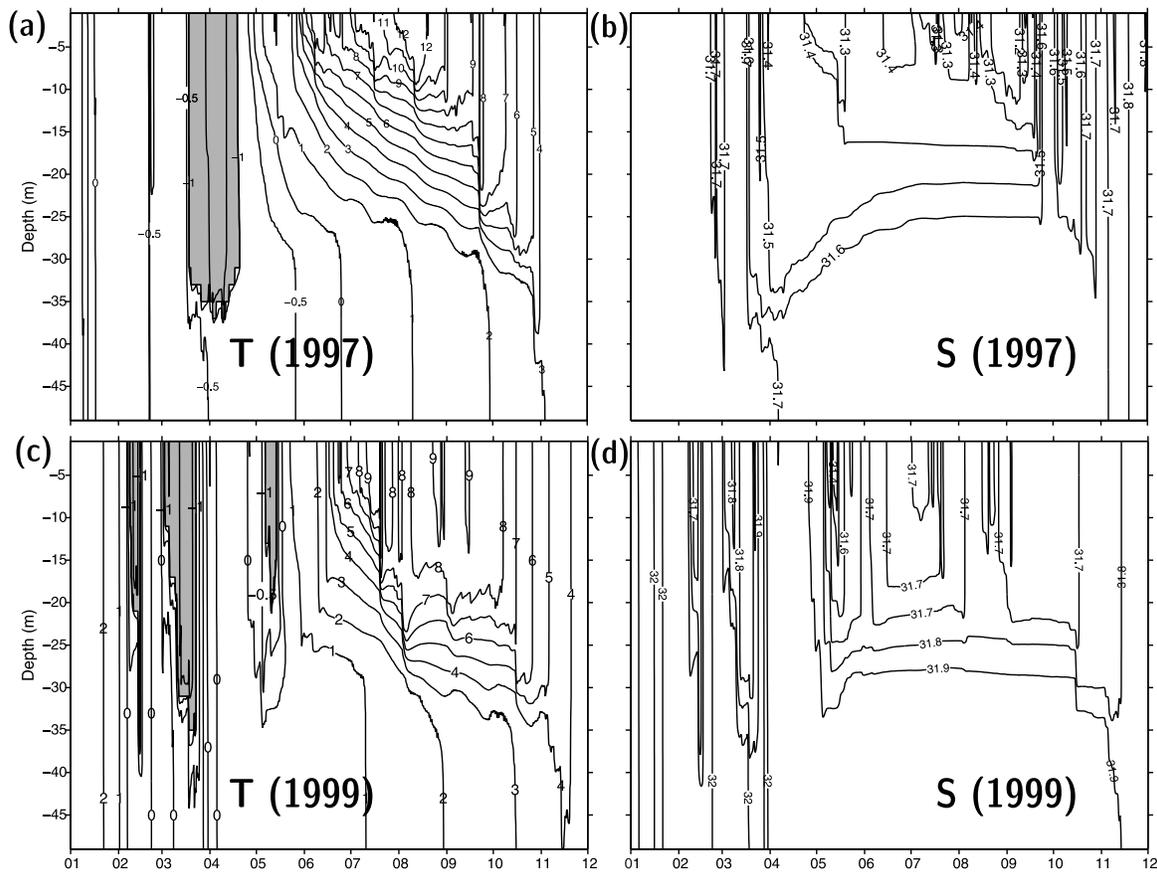


Figure 2. Modeled temperature and salinity in 1997 and 1999. The shaded area has less than -1°C temperature and indicates sea ice presence.

mum photosynthetic rates at freezing temperatures for a natural population of sea ice algae in Hudson Bay [Rochet *et al.*, 1985].

3. Results

[9] In 1997, the modeled physical environment (Figures 2a and 2b) showed near-freezing temperature and decreasing salinity in late March to early April that was coincident with the period of sea ice presence from mid-March to April 10 (Figure 3a). This generated a gradually decreasing mixed-layer depth that favored the development of a phytoplankton bloom. The surface Chlorophyll a (Chl a) bloom (Figure 3a) was captured by OCTS (Ocean Color and Temperature Scanner), operated only from mid-1996 to mid-1997 [Saitoh *et al.*, 2002]. The surface water bloom started around April 1 according to the OCTS data, 10 days before the ice was gone, and grew rapidly, peaking on April 13. The bloom observed by OCTS peaked at $29.7 \pm 19.5 \text{ mg Chl a m}^{-3}$, close to the $30 \text{ mg Chl a m}^{-3}$ observed in the vicinity of ice by Alexander and Niebauer [1981] on the mid-shelf to the northwest of M2 on May 21–25 1975, but the magnitude quickly dropped to around $20 \text{ mg Chl a m}^{-3}$ several km away from the ice edge. The model showed a peak magnitude of $140 \text{ mg Chl a m}^{-3}$ in the bottom layer of the sea ice and $18 \text{ mg Chl a m}^{-3}$ in the surface 2m layer (Figure 3a), a sharp gradient of Chl a at the water-ice interface; the OCTS data showed an algal biomass between

those two. The fate of ice algae after their release into the water column was quite different for the two cases (Figures 3a and 3b). Comparison of the two cases with OCTS (Figures 3a and 3b) suggests that case 1 (growth of ice algae in the water) was more realistic, though far from perfect, in describing the timing, magnitude and duration of the bloom than was case 2 (no growth of ice algae in the water column).

[10] Although the OCTS data indicated that the bloom came to a quick end by April 27, a subsurface bloom at 12 m, 24 m and 44 m (Figure 4) lasted until early May. The modeled timing, duration and magnitude of the case 1 bloom (Figures 4a–4c) matched the mooring fluorometer data at 12 m and 24 m very well. At 44 m, the fluorometer data showed two peaks; the modeled results showed a late start and a lower magnitude for the first peak, but generally matched the second peak very well. The fast decline of the algal bloom in early May was caused by increased zooplankton grazing, and increased temperature and light intensity favored open water phytoplankton species over ice algae. As a comparison, case 2 (Figures 4d–4f) mismatched the fluorometer data (Figures 4d–4f), both in terms of starting time and duration of the bloom. The differences in taxonomic composition of the phytoplankton species between the two cases revealed that the phytoplankton bloom in 1997 was seeded by ice algae released from the sea ice rather than by the pelagic diatom and flagellates. The ice algal cells released from the sea ice can grow well in the

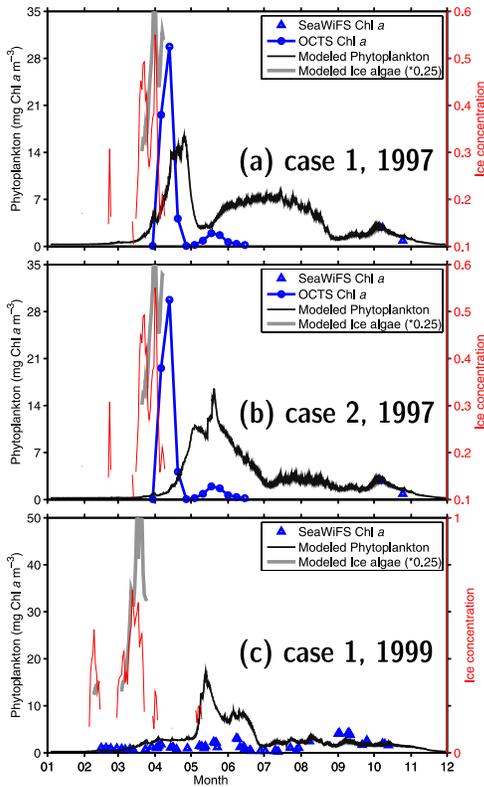


Figure 3. SSM/I ice concentration, simulated ice algae in sea ice and total phytoplankton (diatom, flagellate and ice algae) in the sea surface layer, remote sensing Chl a: (a) case 1 of 1997, (b) case 2 of 1997, and (c) case 1 of 1999.

cold open water, the stratification kept the algae in the upper water, and zooplankton grazing was low. This is consistent with several criteria of ice algal seeding in other ice-covered regions as discussed by *Garrison et al.* [1987] and *Leventer* [2003].

[11] In 1999, the sea ice was present at the mooring site during three separate periods (Figure 3c): early to mid-February, mid-March to early April, and early May. The daily Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Chl a concentration data did not capture any bloom in 1999 (Figure 3), which demonstrates that using satellite data to estimate primary production may underestimate primary production in the water. The model results showed that ice algae bloomed in the sea ice only during the March sea ice period (Figure 3c). No substantial phytoplankton accumulation in the water occurred (Figures 4g–4i) in the same period due to low light levels and consequently slow growth rate. In addition, after the ice retreat in early April (15 days earlier than in 1997), both temperature and salinity increased (Figures 2c and 2d) and (along with wind) resulted in a deep mixing that retarded the further growth of the bloom. This is in accordance to field data collected in the cold March 23–24 of 1976 [*Alexander and Niebauer*, 1981] where chlorophyll a concentrations along a section from the shelf bread to the west of M2 showed only a small rise of $1 \text{ mg Chl a m}^{-3}$ at the ice edge. These results suggest that sea ice retreat in mid-March does not necessarily lead to ice-associated blooms as proposed in the OCH hypothesis [*Hunt et al.*, 2002]. Our model suggests that ice melt induced low-salinity stratification must not be followed by a strong mixing event that would destroy the stratification to sustain substantial algal growth. An ice-associated bloom initiated in mid-March or later might not grow to the typical

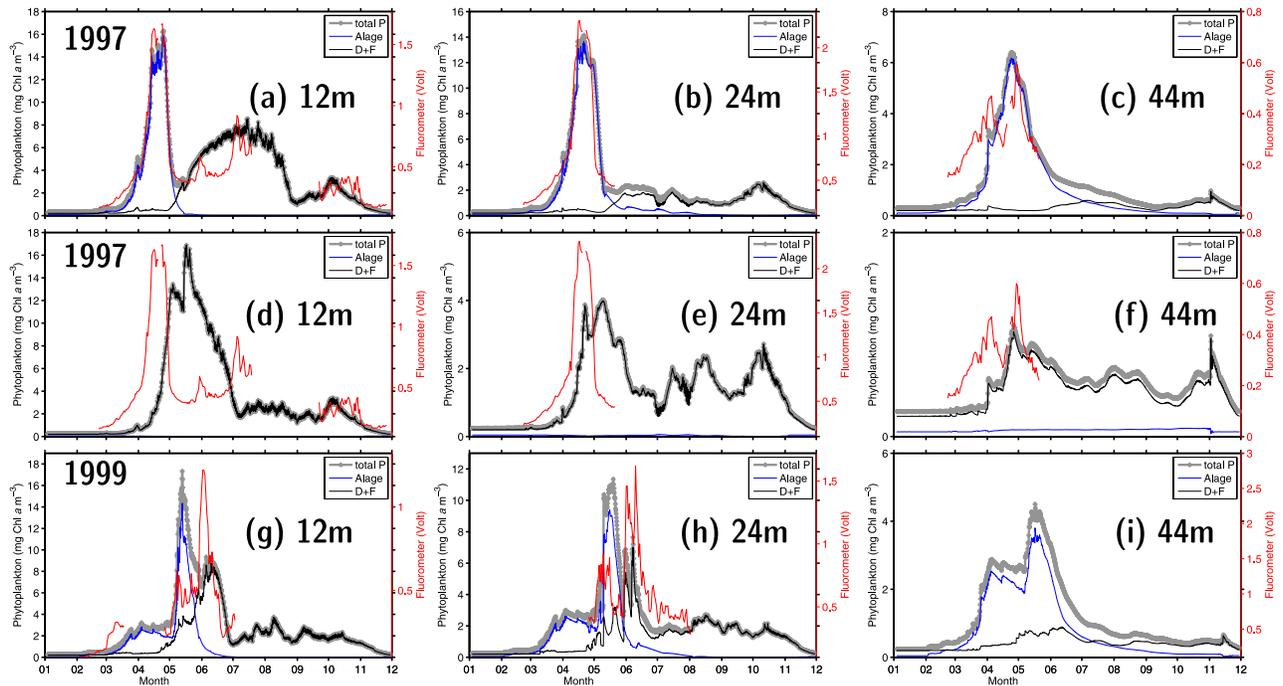


Figure 4. Comparison of fluorometer with simulated total phytoplankton at 12 m, 24 m and 44 m for (a, b, and c) case 1 of 1997, (d, e, and f) case 2 of 1997 and (g, h, and i) case 1 of 1999. The ice algal concentration, diatom and flagellate concentration (D + F) are also included.

level of a phytoplankton bloom if strong vertical mixing follows in the region from early to mid-April as in 1999.

[12] Although the third sea ice appearance in early May 1999 was short, it did initiate the start of the phytoplankton bloom. The model very well captured the starting and ending time of the phytoplankton bloom, as compared with fluorometer data at 12 m and 24 m (Figures 4g and 4h). Although the magnitudes did not match well, both model and data showed two peaks of bloom, the first dominated by a bloom of ice algae, followed by a bloom of pelagic flagellates and diatoms. The two peaks were closer in time than in 1997 as May conditions in general are favorable for a phytoplankton bloom with a thermal stratification forming and high light levels.

[13] The simulated annual net primary production (NPP, algorithm of Jin *et al.* [2006a]) of our model for the six year period 1995–2000 (data presented in order) was 101, 120, 89, 119, 115 and 109 g C m⁻² for case 1, within the range of the previous observational estimates of 60–180 g C m⁻² [Springer *et al.*, 1996] for the southeastern Bering Sea. Year 1997 had the lowest NPP because the warm and shallow summer mixed layer caused pronounced nutrient limitation in the euphotic zone. The ice algal production in the water column accounted for 42% and 29% of NPP in 1997 and 1999, respectively. Assuming no ice algal growth after their release into the water column (case 2) had little impact on the yearly NPP estimate with maximum differences of 5 to 7% in 1998 and 2000. This indicates that yearly NPP is mainly regulated by nutrient supply in the southeastern Bering Sea, which agrees with Hunt and Stabeno's [2002] results based on various data from 1970s to 2000.

4. Ecological Implications of Ice-Associated Blooms

[14] In the Bering Sea, the ecosystem shift in response to climate changes is being magnified and complicated by ice-associated algal blooms. This study suggests that the ice-associated bloom is sensitive to physical conditions ranging from short-term weather events to long-term climate change. The PDO climate index (Figure 1b) showed a shift from decadal oscillation in the 1970s/80s to higher frequency quasi-decadal (~5 years) oscillation in the last decade. The increasingly variable climate tends to cause unexpected ecosystem changes through unusual, episodic weather events [Bond and Overland, 2005] and the occurrence of ice-associated bloom vs. open water bloom [Hunt and Stabeno, 2002]. An ice-associated bloom in May or later occurred more often before the 1976/77 'regime shift', and 1999 can be seen as a sudden intrusion of 'cold regime' in a decades-long 'warm regime'. These sudden changes might be important because they leave less time for the ecosystem to adjust than do changes caused by gradual global warming [Grebmeier *et al.*, 2006]. We have developed the 1-D ice-ocean ecosystem model to simulate ice-associated blooms in the Bering Sea. Based on our model results, the bloom of ice released algae in the southeastern Bering Sea might have strong influences by changing the taxonomic composition of phytoplankton species, the timing and duration of primary production, and the depth at which such production occurs. Those changes can cause the pelagic ecosystem to alternate between primarily bottom-up control in cold

regimes to primarily top-down control in warm regimes [Hunt and Stabeno, 2002], and can impact food web structure in the polar waters. Differences in the composition and magnitude of sea ice algae might cause changes in the suitability of spring blooms for zooplankton grazing and thus directly impact ecosystem responses. Further observational and modeling work is needed to link the variations of primary production to variations of secondary production - fish and fisheries harvest, sea birds, and sea mammals. Such links will be important to assess whether or how ice-associated blooms contributed to the unexpected and dramatic declines of AYK salmon runs from 1997 to 2002 as indicated by the co-occurrence in space and time.

[15] In order to predict the ecosystem implications of new phytoplankton species introduced by advection of sea ice, it is important to understand which algal species are incorporated into sea ice as it forms in the autumn and winter, and where and when this incorporation occurs.

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