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Settlement patterns of snow crab associated with warm and cold years in the Eastern Bering Sea

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Abstract

An individual-based model for snow crab (*Chionoecetes opilio*) larvae coupled to a hydrodynamic model was implemented to study the transport and settlement patterns associated with warm (1979) and cold (1990) years in the Eastern Bering Sea (EBS). Oceanographic conditions from the hydrodynamic model were compared to near bottom temperature data from surveys (NBT) in order to validate the hydrodynamic model output. Both years presented oceanographic conditions with contrasting temperatures during the hatching, transport and settlement period (May to October) of snow crab. Several simulation experiments to assess the trajectory and potential settlement areas of virtual larvae released in the middle and outer domain of the EBS were performed. The simulation experiments considered initial conditions of crab larval release based on historical distributions of adult females inferred from annual bottom trawl surveys. The simulations experiments were run between May and October, releasing particles in eight regions. The behavior incorporated in the individual-based model for snow crab larvae included the release of particles representing snow crab larvae near the bottom, their movement upward in the water column to the mixed layer and then retention in the mixed layer until the time of potential settlement. Initial simulations showed that 1979 and 1990 presented similar overall potential settlement patterns, but very different temperatures patterns. Even though current patterns in both years are quite similar, the areas of potentially successful settlement differ due to these temperature differences. No transport towards the southeast (historical distribution areas) was seen in these simulations. These results may have implications for success of settlement of snow crab under different scenarios of climate change.

Introduction

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 catch 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).

Snow Crab
All Districts

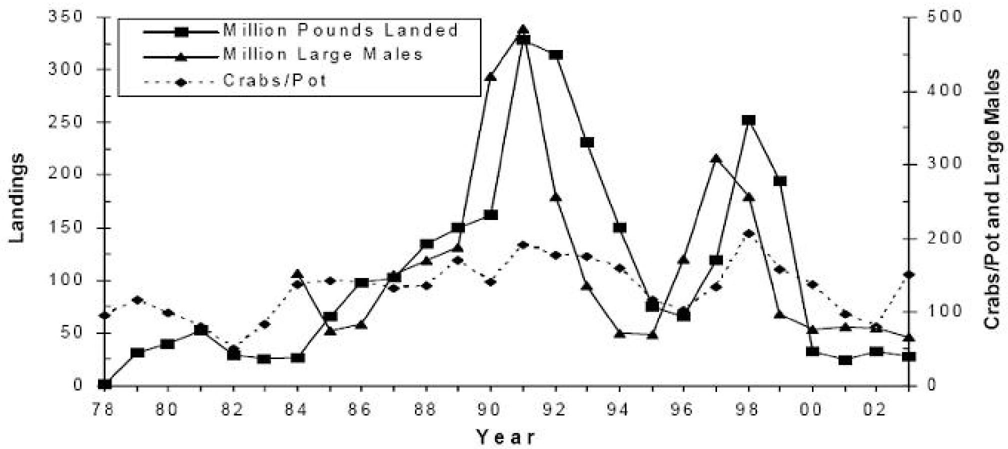


Figure 1. US Landings in millions of pounds, CPUE as crabs /pot-lift, and the abundances of large male snow crab (*C. opilio*) millions (all districts combined), estimated from NMFS trawl surveys (Rugolo et al., 2003).

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 factor 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).

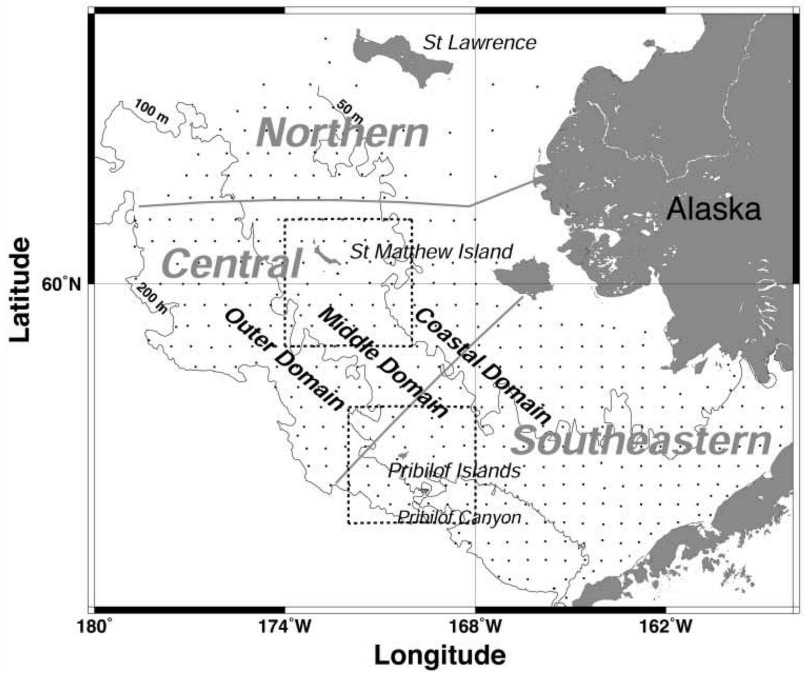


Figure 2. The Eastern Bering Sea (EBS). Dots indicate NMFS survey stations where snow crab was observed at least once during surveys conducted between 1975-2001. Dashed rectangles around the Pribilof Islands and St. Matthew Island that were defined to study the relationship between ontongenetic changes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

Changing climatic conditions in the Bering Sea may also affect recruitment of snow crab in the Bering Sea in coming years. According to Stabeno et al. (In Press), in the last decade, the southeast Bering Sea has seen average temperature increases of 3°C, and reduction in the southward extent and duration of sea ice. Sea ice may provide several mechanisms for affecting recruitment of snow crab: (1) As sea ice melts, an ice edge bloom can form, which has been hypothesized to be a food source for larval snow crab (Somerton 1981). If the ice edge retreats northward, or there is an increase in ice-free years in the Bering Sea, survival of larval may (a) be better to the north, or (b) be negatively impacted if no ice edge bloom occurs. (2) Melting ice cools the water column to temperatures which may be preferable to settling juvenile snow crab. Juvenile snow crabs are known to be stenothermic, with a temperature preferendum below 2°C, and most likely also above 0°C (Dionne et al. 2003). (3) The extent of the ice edge correlates well with the size of the cold pool in the Bering Sea (Stabeno et al. In Press). The extent of the cold pool, which contains temperatures (at the bottom) of less than 2°C, within the juvenile snow crab temperature preferendum, may affect the habitat area available for immature snow crab.

There may be factors affecting the warming seen in the southeast Bering Sea over the past decade, other than loss of sea ice. Whatever the mechanisms (see Stabeno et al., In

Press), the implications for snow crab may be critical in affecting recruitment in coming years, if the Bering Sea continues to warm.

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. Although oceanographic conditions in the SEBS are becoming better understood due to increases in instrumentation and studies, the central and northern Bering Sea have been less well documented. Also, until now, no circulation model was available to analyze advection or temperature patterns over the eastern and northern Bering Sea. In the EBS, modeling efforts have been 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 temperature, 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 and temperature on the early life history dynamics of crab using a mechanistic approach. The use of a high resolution hydrodynamic model to simulate current and temperature 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.

The main objective of the present work is to study the effects of transport and survival of snow crab larvae by using an IBM coupled to a hydrodynamic model, along with biological information on crabs in the EBS. We describe the initial version of the crab individual-based model, and the results of a simulation done to compare patterns of transport and potential settlement during 2 years of contrasting temperature.

Methods

We utilize hydrographic output (currents and temperature) from two years (1979 and 1990) of ROMS simulations, performed on a 10 km grid which includes the Bering Sea. Details of these simulations can be found in Curchitser et al. (2005). These years were chosen as they represent significantly differing temperature scenarios, with 1979 being a relatively warm year, and 1990 a relatively cold year. These outputs are used to drive the individual based model (Fig. 3), which is run offline from the ROMS model.

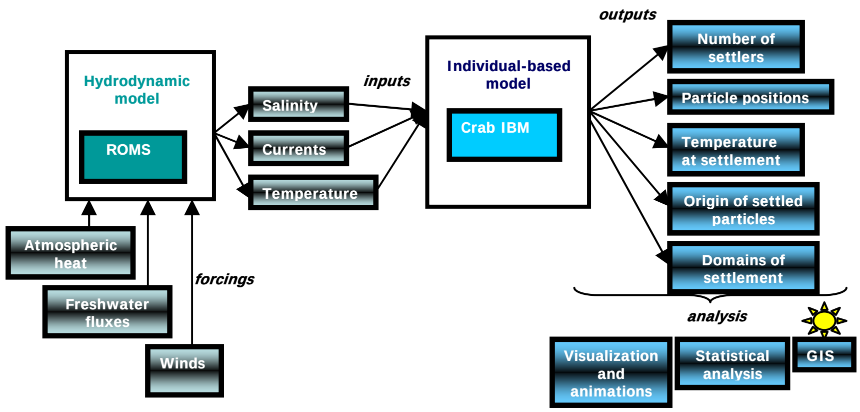


Figure 3. Schematic of the coupling between the ROMS hydrodynamic model and the crab IBM, with outputs of the IBM and analysis shown.

Near-bottom temperatures (NBT) output from the ROMS model are compared to those sampled during the 1979 and 1990 NMFS bottom trawl surveys (Stevens et al. 2002) for similar periods. Surveys follow a systematic sampling design, where stations are regularly spaced over a 20 nautical mile (nmi) × 20 nmi grid and sampled every year (Fig. 2). Temperature data was recorded to a precision of 0.1 °C between May-August and June-August of 1979 and 1990, respectively.

In the crab IBM, individual larvae are treated as particles with vertical movement capability, that are tracked through space using a Java-based float tracking tool. Larvae are released near the bottom, migrate to the mixed layer and are retained there through the period of pelagic transport (Fig. 4). Larvae are released from eight historical distribution areas in the middle and outer domain of the Eastern Bering Sea (Fig. 5). The release period lasts for two months (May 1st to July 1st). Settlement is set to occur 90 days after release. The model runs until October 1st. Trajectories to the potential settlement location were followed. Particle positions, the number of settlers, and temperature at potential settlement location, as well as the origin of the settled particles were recorded.

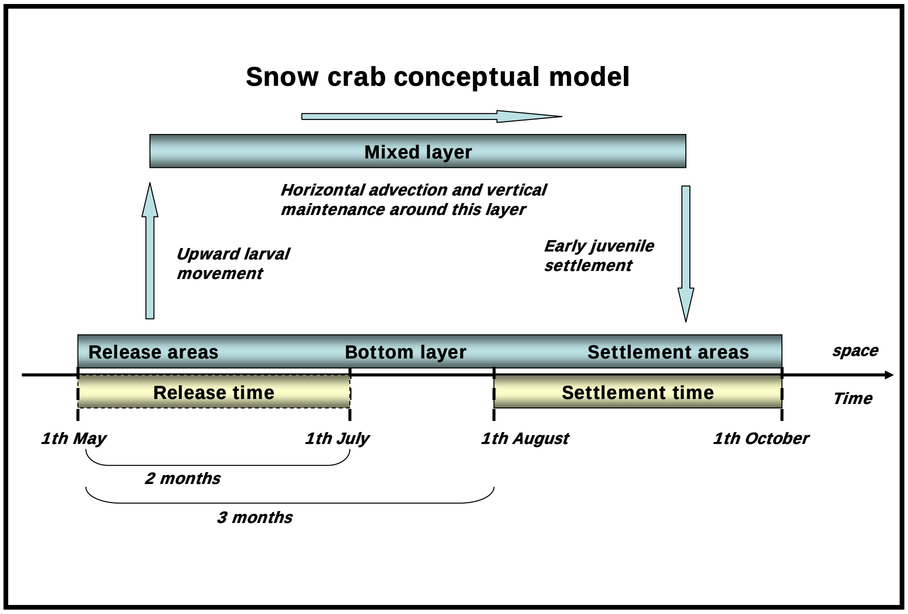


Figure 4. Snow crab larval transport conceptual model.

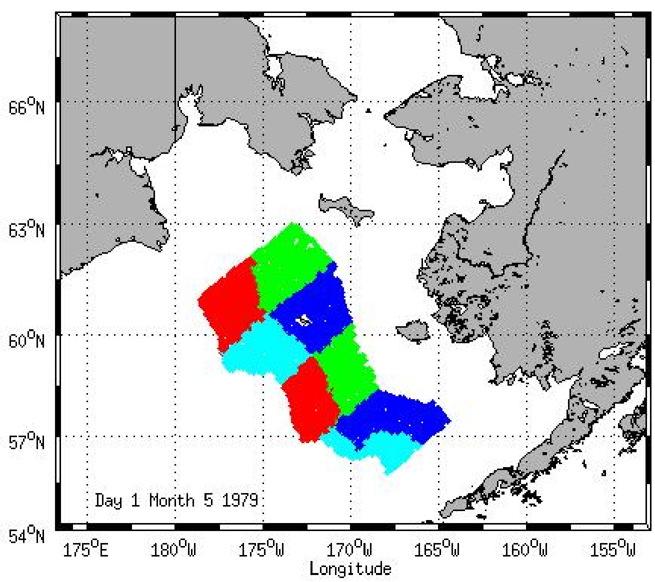


Figure 5. Release areas of larval snow crab in the Bering Sea for this simulation.

Results

ROMS vs. data temperature comparison

Inspection of Figures 6 and 7 indicate that the ROMS model (Fig. 7) does a good job of reproducing the general temperature distributions as shown by the data (Fig. 6), with temperatures during July of August, 1979 warmer than those of the same months in 1990. The absolute temperatures shown by the model may be slightly higher in the nearshore areas than those shown in the data.

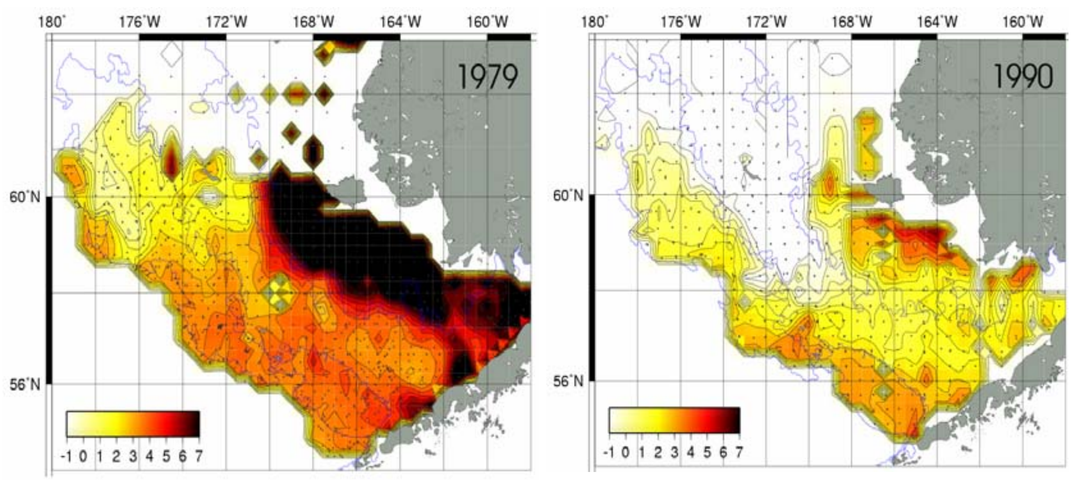


Figure 6. Near bottom temperature data from NMFS bottom trawl surveys from 1979 (May-August) and 1990 (June-August).

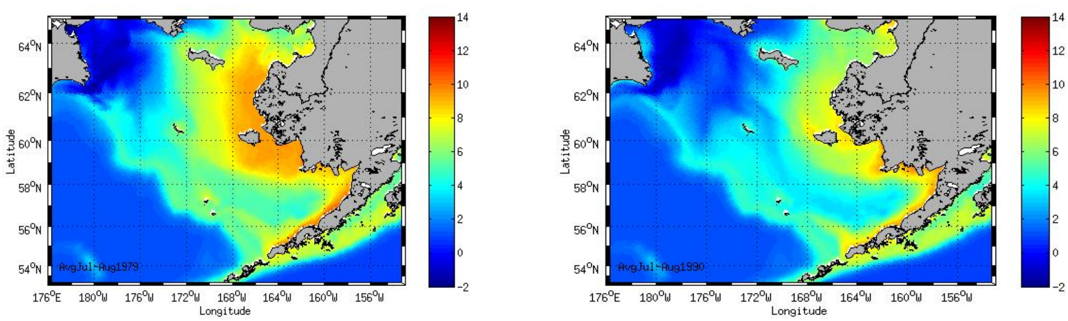


Figure 7. Near bottom temperature data from ROMS model over the period July 1st to August 30th for (left) 1979, and (right) 1990.

Maps of settlement and temperature

From inspection of the modelled density of settlers in the potential settlement regions for 1979 (Fig. 8a, left) and 1990 (Fig. 8b, left), it can be seen that the region of potential settlement does not vary significantly between the two years. There were a few small differences: a somewhat higher simulated density of juveniles north of St. Lawrence in

1979; a lower density there in 1990. It can also be seen from Figs. 8a and b that no larvae were transported to the southeastern most regions. In fact, larvae were not transported to the southeast from their original locations at all. Temperatures over the potential settlement domain for each year do vary (Figs 8a and 8b, right), with the region where temperatures are > 10°C much broader in 1979, and the region < 4°C much broader in 1990.

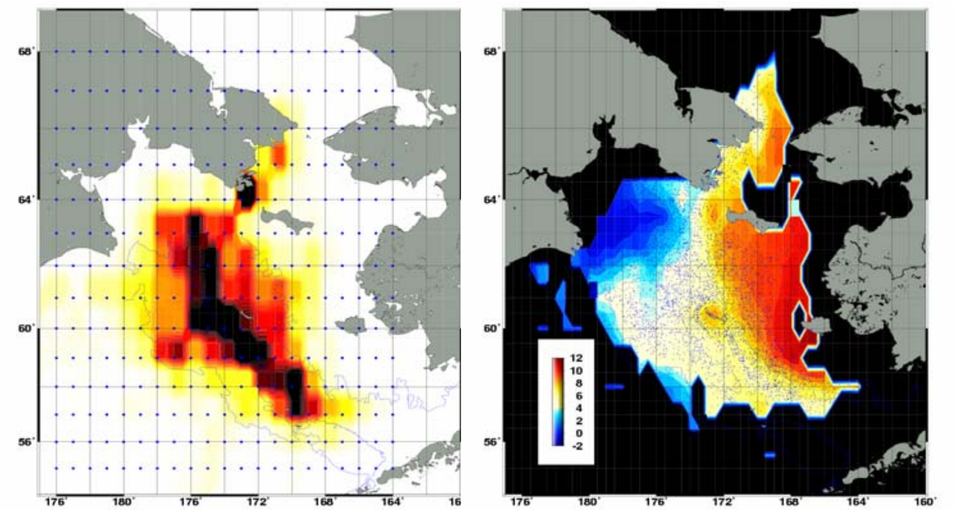


Figure 8a. Maps of modelled density of settlers over the potential settlement region (left) and temperature over the domain for 1979. Temperature in °C.

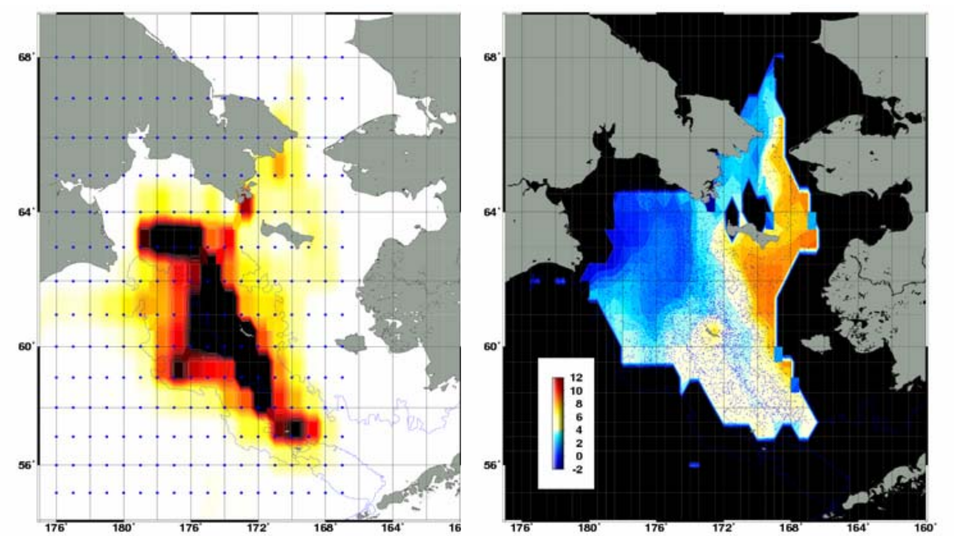


Figure 8b. Maps of modelled density of settlers over the potential settlement region (left) and temperature over the domain for 1990. Temperature in °C.

Snow crab settlers are most often found within a narrow region of temperatures (0 to 2°C) (Dionne et al., 2003). In Fig. 9a we see the modeled region of potential settlement of snow crabs in 1979, with temperature ranges in each subregion. It can be seen that the majority (75%) of this region shows temperatures that are > 2°C. Less than 10% of settlers are found in the region where the temperatures are < 0°C. Slightly more are found within the region where settlers are thought to be most successful, ie. between 0 and 2°C.

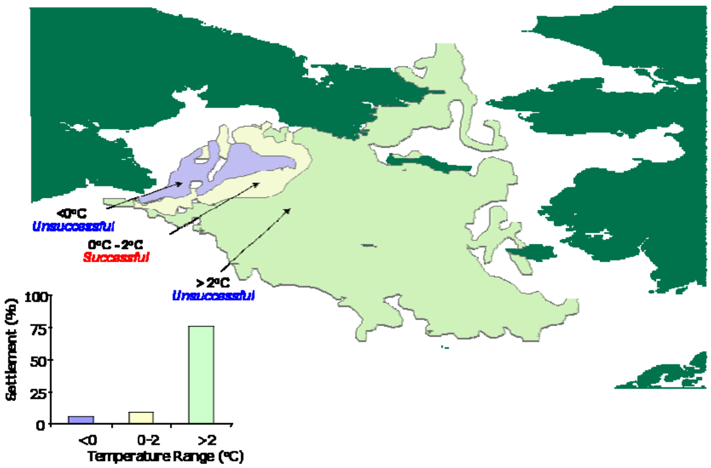


Figure 9a. Polygons representing temperatures in different areas at settlement in 1979. Bar chart at lower left shows the percent of potential settlers within each temperature zone.

In Fig. 9b, which shows the modeled region of potential settlement of snow crabs in 1990, with temperature ranges in each subregion, we see that the percent of potential settlers within the region where temperatures are between 0 and 2°C is much higher than in 1979 at between 25 and 30%.

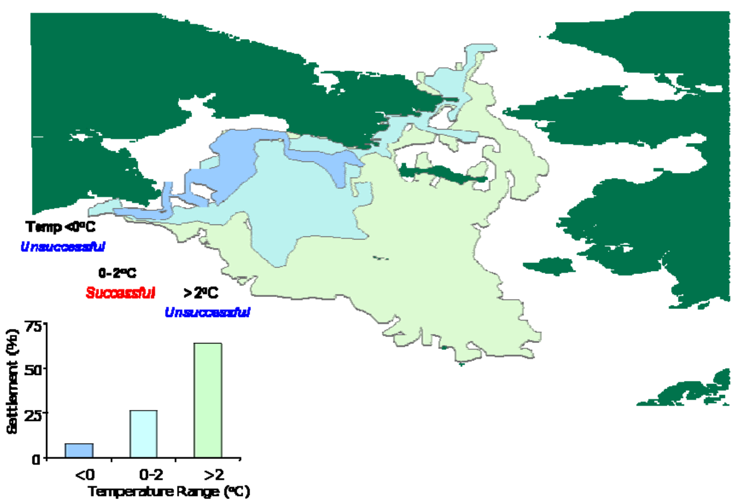
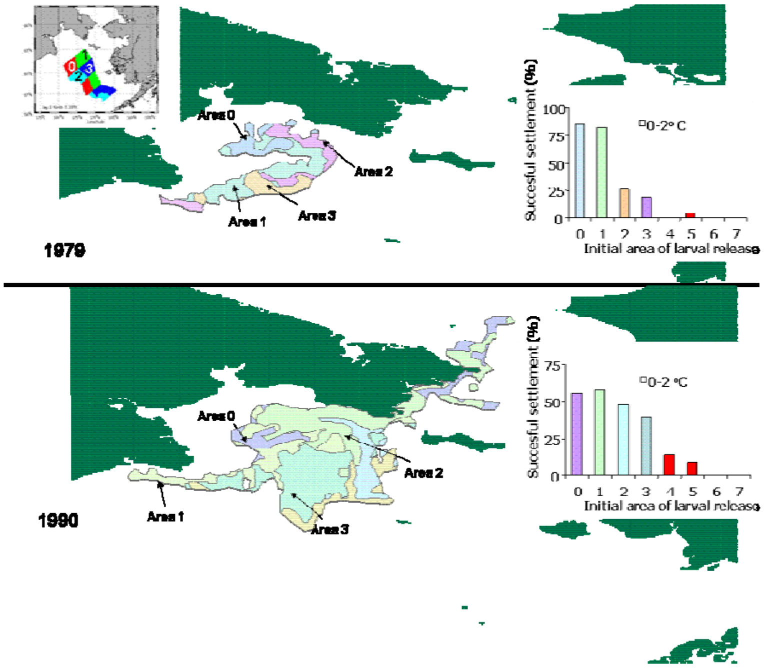


Figure 9b. Polygons representing temperatures in different areas at settlement in 1990. Bar chart at lower left shows the percent of potential settlers within each temperature zone.



In Fig. 10, we can see that in 1979, most of the potential settlers found within the "successful" temperature area were released in zones 0 and 1 of initial release, ie. the northernmost of the eight historical areas. In 1990, on the other hand, the largest percentages of potential settlers came from areas 0-3, the northern half of the initial distribution area. Successful juveniles came, then, from a much broader region in 1990 than in 1979.

Figure 10. Maps showing the areas of initial release of the "successful" potential settlers for (top) 1979 and (bottom) 1990. Inset on the upper left indicates the eight original areas of release of larvae. Bar charts on the right show the percentage of successful settlers from each original release region.

a.

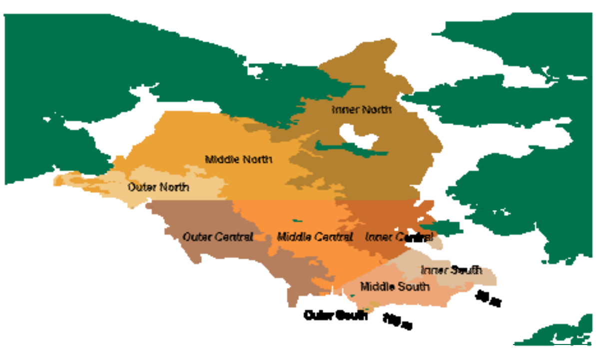


Figure 11a shows the oceanographic domains in the eastern Bering Sea. Figure 11b shows the domains where successful settlers were found in 1979. It can be seen that in that year, successful settlers were found only in the outer north and middle north domains. In 1990 (Fig. 11c), however, successful settlers were found in five domains (the outer, middle and inner north, and the outer and middle central).

Figure 11a. Oceanographic domains in the eastern Bering Sea. Successful settlement regions divided by oceanographic domains for b. 1979, and c. 1990.

b.

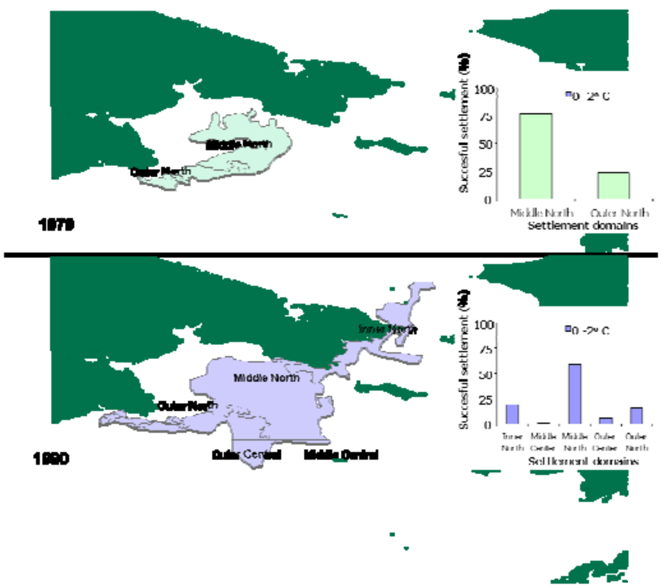


Figure 11b. Oceanographic domains where successful settlers were found in 1979.

Figure 11c. Oceanographic domains where successful settlers were found in 1990.

c.

Discussion

Snow crab settlers are frequently found in regions with a narrow temperature range (0 to 2°C) (Dionne et al., 2003). Our assumption in this work is that this range of temperatures is advantageous for survival. It is not known why settling crabs are found for most part in regions where the temperature is in this range. It may be that snow crab juveniles choose to settle in areas with this range of temperatures, or that we seem them there due to better survival. We have defined areas where settlement stage early juvenile snow crabs are found that show temperatures within this range as “potentially successful settlement regions”.

We see small differences in overall transport or settlement locations of all snow crabs released in 1979 and 1990. It is interesting to note that no transport of larvae to the southeast from their location of origin was seen. More simulations, under different scenarios of circulation, are needed to test this effect are to come to a conclusion about the likelihood of repopulation of historical distributions in the southeast.

We do see, however, significant differences in the size of the regions of potentially successful settlement between the two years. The warm year, 1979, shows a much smaller region of potentially successful settlement than does the cold year, 1990. Also, potentially successful settlers from the warm year come from a very narrow range of release sites, whereas those in the cold year originate over a broader region of the eastern Bering Sea.

These results indicate a mechanism whereby temperature may have a significant role in recruitment success of snow crab in the Bering Sea, through the size of potential settlement habitat, and the size of the spawning region that can produce successful settlers. These experiments are simple but relevant because they lead us to understand the potential of settlement success under different climatic scenarios. It seems that 1990, a cold year, presented better conditions for settlement than 1979, a warm year. Continued warming and the potential for loss of sea ice in the Bering Sea may, therefore, have detrimental effects on snow crab recruitment.

Future experiments with this model will consider the differences in female reproductive output (FERO) for individual years, and more realistic spatial distributions of larval release in each year. We will incorporate growth rates dependent on temperature to observe differential development and later effects on settlement. More years of contrasting temperatures will also be considered to verify these results.

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